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ABSTRACT

QoS CONSTRAINED CELLULAR AD HOC AUGMENTED NETWORKS

by
Chi-Tung Chen

In this dissertation, based on different design criteria, three novel quality of service (QoS) constrained cellular ad hoc augmented network (CAHAN) architectures are proposed for next generation wireless networks. The CAHAN architectures have a hybrid architecture, in which each MT of CDMA cellular networks has ad hoc communication capability. The CAHAN architectures are an evolutionary approach to conventional cellular networks. The proposed architectures have good system scalability and high system reliability.

The first proposed architecture is the QoS constrained minimum-power cellular ad hoc augmented network architecture (QCMP CAHAN). The QCMP CAHAN can find the *optimal* minimum-power routes under the QoS constraints (bandwidth, packet-delay, or packet-error-rate constraint). The total energy consumed by the MTs is lower in the case of QCMP CAHAN than in the case of pure cellular networks. As the ad hoc communication range of each MT increases, the total transmitted power in QCMP CAHAN decreases. However, due to the increased number of hops involved in information delivery between the source and the destination, the end-to-end delay increases. The maximum end-to-end delay will be limited to a specified tolerable value for different services. An MT in QCMP CAHAN will not relay any messages when its ad hoc communication range is zero, and if this is the case for all MTs, then QCMP CAHAN reduces to the traditional cellular network.

A QoS constrained network lifetime extension cellular ad hoc augmented network architecture (QCLE CAHAN) is proposed to achieve the maximum network lifetime under the QoS constraints. The network lifetime is higher in the case of QCLE CAHAN than in the case of pure cellular networks or QCMP CAHAN. In QCLE CAHAN, a novel QoS-constrained network lifetime extension routing algorithm will dynamically select suitable ad-hoc-switch-to-cellular points (ASCPs) according to the MT remaining battery energy such that the selection will balance all the MT battery energy and maximizes the network lifetime. As the number of ASCPs in an ad hoc subnet decreases, the network lifetime will be extended. Maximum network lifetime can be increased until the end-to-end QoS in QCLE CAHAN reaches its maximum tolerable value.

Geocasting is the mechanism to multicast messages to the MTs whose locations lie within a given geographic area (target area). Geolocation-aware CAHAN (GA CAHAN) architecture is proposed to improve total transmitted power expended for geocast services in cellular networks. By using GA CAHAN for geocasting, saving in total transmitted energy can be achieved as compared to the case of pure cellular networks. When the size of geocast target area is large, GA CAHAN can save larger transmitted energy.

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To my parents
To my wife and daughter
To my family

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CHAPTER 1

INTRODUCTION

1.1 Third Generation Wireless Systems

The second generation (2G) wireless systems such as code division multiple access (CDMA) and global system for mobile communications (GSM), have brought mobile telephony to an impressive worldwide market. The third generation (3G) wireless systems, including cdma2000, wideband CDMA (W-CDMA), and the universal mobile telecommunications system (UMTS), are currently under development around the globe. Some of the objective of 3G system are [1]:

- To provide audio, data, video, and particularly multimedia services.
- To provide a wide range of telecommunications services requiring user bit rates of up to 2Mb/s.
- To provide the same quality of service (QoS) to roaming users as they enjoy in their home environment.
- To provide services via handheld, portable, vehicle-mounted, movable, and fixed terminals in all service environments as well as different radio environments provided the terminal has the necessary capabilities.

In order to support these services, 3G systems bring a fundamental change since they will primarily be using packet switching instead of circuit switching, even though the networks have to interwork with the existing circuit-switched cellular infrastructure [1]. Packet switching will be common for delay-tolerant as well as delay-intolerant applications, and as a result the QoS metrics (delay, throughput, loss, and jitter) will

become increasingly important, at least for delay-sensitive applications.

1.2 Multihop Cellular Networks

When the demand for wireless services increases, the capacity in a single cell of a cellular system becomes insufficient and certain QoS requirements (e.g., throughput and delay) can no longer be met. One technique to support high data rate transmissions in traditional cellular networks is cell splitting. Cell splitting is the technique of subdividing a congested cell into smaller cells, each with its own base station (BS) [9]. The technique increases the system capacity of the cellular system but the network provider has to pay for increasing the number of BSs and additional infrastructure. To avoid this penalty, an evolutionary approach, referred to as multihopping, is proposed [10-15]. In [10], a multihop cellular network (MCN) architecture is proposed as an attractive alternative to conventional single-hop cellular networks. The MCN has localized ad hoc networks in a cell, and mobile terminals (MTs) can help BS to relay packets. MCN provides a method to increase the spatial reuse of the channel. The work in the article focuses mainly on the system throughput of MCN. In [11], an ad hoc GSM (A-GSM) cellular network is proposed. In the A-GSM network, MTs are capable of relaying calls and are used to increase system capacity. The A-GSM network can provide efficient communication performance at dead spot locations and expand its area coverage while maintaining the transmission range of BS. An MT participating in A-GSM protocol has to perform the measurement of radio links, which include the link to the BS and the links to each of its neighbor nodes. The decision of direct or multihop transmission from the serving BS is made based on the signal strength measurements taken at the MT. In [12], an integrated

cellular and ad hoc relaying system (iCAR) provides a number of ad hoc relaying stations (ARSs) at strategic locations, which can be used to relay signals between MTs and BSs. The traffic can be diverted from a congested cell to another relatively under-loaded cell by using the ARSs. This helps to dynamically balance the traffic among different cells and circumvent the traffic congestion. Main issues in this article relate to load balancing. In [13], the authors propose a hybrid wireless network model, in which several fixed relaying stations are placed in each cell sector to improve the capacity of existing cellular networks. A packet arriving at the BS will be transmitted to either a relaying station or directly to a user. In [14], the proposed hybrid model uses a peer-to-peer network model in tandem with a conventional cellular infrastructure. By default, the network operates in the peer-to-peer model. When a traffic flow served in the peer-to-peer mode experiences low throughput, the flow will be switched to the cellular mode to relieve the traffic congestion. However, traffic flows are periodically reverted back to the peer-to-peer mode. In [15], the article proposes a simple multihop architecture and examines some techniques by which the system capacity (throughput) of multihop cellular networks can be augmented. Diversity techniques, multi-element arrays, space-time coding, and multiuser detection are discussed as some of the techniques that could reduce the interference due to packet relaying.

Although there have been many works in the area of multihop cellular networks so far, most previous works focus mainly only on system capacity (throughput) and load balancing capacities of the proposed architecture. Moreover, these works are still only based on 3G concepts, and some even didn't consider about QoS issue.

1.3 The Research Motivation and Objective

The motivation of this research is to propose a next-generation architecture that is designed to

- 1) Achieve the optimal minimum total transmitted power under QoS constraints. The side effect of such gain is the network capacity increase.
- 2) Dynamically balance MT battery energy and extend the network lifetime under QoS constraints: The network lifetime is defined as the time at which an MT runs out of its battery energy for the first time within the entire network, as defined in [69-71].
- 3) Support less total transmitted power for location-aware geocast service.

1.4 The Concepts of the Fourth Generation Wireless Systems

With commercial development of 3G systems proceeding, the research community turns its attention to the fourth generation (4G) systems. While 4G technology is not as well defined as 3G, there is an emerging consensus that it will rely on Internet protocols and offer bit rates that are an order of magnitude higher than those of 3G systems [16]. The goal for the fourth generation includes support for interactive multimedia services like teleconferencing, global mobility, service portability, and the same telephone quality as the current wireline networks. However, it is not necessary to design a single network that is optimized for all the existing and future services. Instead, it is possible to use a combination of several bearer networks, each of which is optimized for some particular services [23]. The decision of selecting the most suitable bearer network could be based on available bandwidth or service classification. Each service is delivered via the network

that is the most efficient to support this service. Moreover, the terminal battery capacity/weight ratio should increase by one order of magnitude compared with terminals used for 3G systems.

A new international initiative that originated in Europe, developing a research agenda for the future of wireless communication, is the Wireless World Research Forum (WWRF). WWRF is an on going forum to develop a common and comprehensive vision for 4G wireless communications [17]. The 4G involves the concept that 4G will be a major move toward ubiquitous wireless communication systems and seamless high-quality wireless services [18]. Ubiquitous communications involves a desire that continues to drive people's expectations of wireless technologies. Current 2G and 3G systems are providing a glimpse of the possibilities. WLAN and WMAN technologies are becoming more prevalent. These approaches and their extensions are striving toward an all-IP network (there is currently no foreseeable alternative; IP is the best integration technology) [17-18]. The multiple networks are able to function in such a way that interfaces are transparent to users and services. New capabilities are needed to provide ubiquitous service. One is clearly that the technology for the functional integration of the multiple networks. A related principle of ubiquitous services is universal technical access. We label this ultraconnectivity [18]. Enough inexpensive access points in enough places, with devices that can seamlessly access those points at the desired data rates and QoS, are required. Ultraconnectivity is enabled by: [18]

- Wireless networks seamlessly operating with other wireless/wireline networks.
- Seamlessness which implies a melting away of access and interface barriers between networks.

- Highly efficient use of the wireless spectrum and resources.
- Flexible and adaptive systems and networks.
- Distributed intelligence and wireless resources.

To avoid the need for frequent recharge of a portable device and the possible limitation in communication capability, the demand for less energy consumption and more spectra will not abate, and next generation will be no exception. Energy efficiency and battery life will be continuously a concern in next generation system [17]. Dynamic spectrum allocation, assignment, and utilization are beginning to be seriously considered.

The technical means to dynamically assign or utilize spectrum involves [18]:

- Highly adaptive modulation and coding technology.
- Multidimensional/hybrid multiple access techniques.
- A spectrum- and resource-aware MAC/link layer
- Flexible networking
- Spectrum awareness and multilayer resource management

From a technological reference point there are four major factors in achieving the degree of integration, flexibility, and efficiency envisioned in 4G. These are "seamless integration", "a high-performance physical layer", "flexible and adaptive multiple access", and "service and application adaptation". 4G network is also adaptive networks since adaptability and convergence of the various access technologies will require the networks to provide access to a number of radio technologies. QoS concepts will continue to evolve toward approaches where QoS is parametric. Network concepts and architectures will evolve to those that include dynamic adaptation to traffic and QoS needs. In 4G, a universal access node would be able to implement a multiplicity of access

technologies, and provide for a wireless multinet network where those technologies are dynamically selected based on a best match to user needs and available resources.

Moreover, location awareness will still play a major role for future wireless network services (APPENDIX C) [17] [19]. There are two types of geolocation techniques, one based on the network and the other on the handset. In network-based solutions, the geolocation information is generally estimated through the timing and arrival angle from the handset. Handset-based techniques are mainly based on satellite signals using the GPS (Global Positioning System). While initially the GPS was mainly for military applications and its commercial use was prohibitively expensive, the recent rapid and massive commercialization of GPS applications has made cost-effective implementations possible. To meet the FCC E911 requirements, the GPS receiver will be a "necessary" and a part of cellular handset. Many companies have proposed the highly integrated versatile GPS receiver for the cellular handset. For example: 1) gpsOne technology, which is proposed by QUALCOMM Inc. [20]. 2) A highly integrated GPS receiver from Texas Instruments Inc. [21]. 3) STORM RFIC GPS receiver from Conexant Systems Inc. [22] 4) assisted-GPS (A-GPS) [7]. The A-GPS location technology has been specified by 3GPP and 3GPP2. A-GPS's accuracy of under 20 m is a very reasonable expectation in 67 percent of calls. Moreover, the hybrid approaches (such as the combination of A-GPS and OTDOA [2]) may be used to further enhance the performance of the location technology. To meet the FCC E-911 accuracy requirements, Qualcomm has produced MSM5100 third-generation CDMA handset, which has the GPS position location capable [20]. The MSM5100 uses the hybrid location approach that combines measurements from GPS and forward/reverse links of a CDMA system to

improve position service availability. This technology has been extensively field tested and deployed in Japan. The MSM5100 will also enable a broad range of future 3G GPS-related services, including commercial tracking services, navigation information, area-specific weather forecasts/traffic reports, and a broad range of entertainment applications.

1.5 Cellular Ad Hoc Augmented Networks for Next Generation Wireless Networks

1.5.1 Our Vision of Next Generation Wireless Networks

Next generation wireless networks will be a heterogeneous wireless networking with a hierarchical overlay of networks of potentially different technologies. Due to the multitude of physical media and multiple air-interface, the 4G system will have non-homogeneous infrastructure with all-IP backbone. Moreover, as peer-to-peer communications emerges as a dominant characteristic of next generation wireless communications, researchers have focused heavily on ad hoc networks as a means for commercial, personal, and home networking. We can say the enthusiasm in recent research efforts implies "the end" of client-server networking for wireless communications. An extreme case is the ad hoc wireless wide area networking architecture demonstrated by the EPFL proposal on Terminodes [24], based on the concept of geodesic packet forwarding in a peer-to-peer fashion. The radical paradigm shift in networking philosophy is arguably fueled by the implicit disappointment in third generation systems that fail to fulfill the objective of "anytime, anywhere" seamless, broadband access to information resources.

When we consider the all-inclusive big picture of next generation wireless access, the definition of 4G is "a network of networks," that includes cellular, ad hoc, local area,

and home networks, to name a few. These different radio access technologies will most probably need to be inter-connected by an IP-based transport layer. How to enable the transition of users from one radio access environment to another is an unsolved problem that requires not only the development of optimal dynamic resource allocation and mobility management techniques, but also standardization of these techniques across the backbone. The published proposals towards this end are few and far in between; however, the significance of the problem is increasingly recognized.

Our vision of next generation networks is one where a user's access to information and communication resources is locally optimized in time and space. In addition, the nature of the requested service will be an input to the selection of access technology. For example, a delay tolerant email transmission can be efficiently served with the peer-to-peer routing while traditional telephony may be best accommodated by the cellular system.

1.5.2 An Overview of Cellular Ad Hoc Augmented Networks

Cellular ad hoc augmented networks (CAHAN) has a hybrid architecture, in which each MT of CDMA cellular networks has ad hoc communication capability. CAHAN is an evolutionary approach to conventional cellular networks. They are proposed as an attractive alternative to single-hop cellular networks to support high data rate transmissions. The communication channels for the ad hoc communication system and for the cellular system are separated in frequency. Each mobile terminal (MT) is capable of relaying message received from one MT to another MT or directly to base station (BS). An MT may have multihop connection to BS or to the destination MT in the same ad hoc subnet.

CAHAN is a simple, novel, and practical wireless networks. CAHAN has the concept of next generation wireless access and differs with the conventional multihop cellular networks in the following respects.

- 1) The hybrid-overlaid architecture of CAHAN can provide seamless internetworking and support anytime and anywhere access for any service. An intelligent MT can dynamically select to access a cellular radio link or ad hoc radio link depending on the availability and the efficient use of the distributed wireless resources (allocated bandwidth, transmission power, and battery energy) for the service.
- 2) CAHAN can regulate the number of hops between the BS and the MTs to adapt to the end-to-end QoS (delay and throughput) requirements for various regions, intervals, and services. When an MT doesn't need to relay/transmit any message, its will rest its ad hoc communication system. If this is the case for all MTs, then CAHAN reduces to the traditional cellular network, i.e. cellular networks are a special case of CAHAN.
- 3) The proposed CAHAN architecture can improve total energy expended for wireless services. Less power on the air in CDMA cellular system will allow more users to enter a cell. Maximum total energy savings can be increased until the end-to-end QoS in CAHAN reaches its maximum tolerable value. Especially, CHAN can find the optimal minimum-power route in the ad hoc subnet which lies on cellular boundary. That couldn't be done by the conventional multihop cellular networks. The optimal route will indicate which neighbor BS will be the best BS for routing the data packets.

- 4) CAHAN can dynamically balance battery energy across the MTs and hence extends the network lifetime. Maximum network lifetime is increased until the end-to-end QoS in CAHAN reaches its maximum tolerable value. Meanwhile, the total traffic loads in the whole networks will also be balanced such that it also can improve the system capacity (throughput), as compared with the traffic-unbalanced cellular system.
- 5) With the help from the resource-aware BS, the CAHAN is able to utilize both centralized and decentralized way for the wireless network construction. CAHAN is a flexible and adaptive network and has the ability of dynamic resource allocation and utilization.
- 6) The proposed CAHAN architecture has good scalability, high reliability and strong robustness. CAHAN can provide highly scalable support for packet routing to large numbers of MTs in the network, even for large network density. Reliability of a network can be defined as the probability that at least 1 path exists between each pair of nodes in this network [75-76]. In CAHAN, a MT can dynamically select to access a cellular radio link or ad hoc radio link depending on the availability of the wireless resources, such that CAHAN has higher system reliability, as comparing with the cellular networks. CAHAN also can find multiple routes between BS and MTs to increase the robustness against failures (This multipath routing scheme is an optional technique in CAHAN).
- 7) To meet the requirements of the FCC E-911, the higher-accuracy GPS approach (or other hybrid location techniques) can be implemented into CAHAN. Moreover, using the location technique, each MT/BS has the ability of the

location awareness such that it can be used to help the resource management, the mobility management, and the network optimization. The location awareness can also be used for other location applications such as geocasting, location tracking, location-sensitive billing, and location-based information services.

A MT in CAHAN is capable of communicating with other MT directly if they are located within a predefined direct radio communication range. If the source MT and the destination MT are in close proximity, a direct connection can be established. MT should constantly monitor the channel quality that they are communicating with. The proposed CAHAN architecture has the full set of functionalities of supporting integrated/packetized voice, data, image, and video service.

CHAPTER 2

QoS CONSTRAINED MINIMUM-POWER CELLULAR AD HOC AUGMENTED NETWORK ARCHITECTURE

2.1 Introduction

Recently, providing IP services in wireless networks is becoming popular. Especially the current maturity of the Internet and the integration of cellular services and the Internet will make delivering information to "high mobility users" possible. In various wireless networks, the architecture of wireless networks has a defining effect on the message transmission mechanism. Message transmission in single-hop cellular networks, where there are fixed network access points, presents a different set of problems than message transmission in multihop ad hoc networks, where there is no network infrastructure. Cellular networks and ad hoc networks have individual advantages. Cellular networks have a simple network model because of the presence of fixed central network access points; ad hoc networks are particularly attractive due to their easy, quick, and economical deployment.

When the demand for wireless services increases, the capacity in a single cell of a cellular system becomes insufficient and certain QoS requirements (e.g., throughput and delay) can no longer be met. In future cellular systems, high data rate wireless services are expected. One technique to support high data rate transmissions in traditional cellular networks is cell splitting. The technique increases the system capacity of the cellular system but the network provider has to pay for increasing the number of BSs and additional infrastructure. To avoid this penalty, an evolutionary approach, referred to as multihopping, is proposed (Section 1.2). Although the performance of multihop cellular

networks has been studied extensively, the previous works focus mainly on the system capacity (throughput) and load balancing capabilities of the proposed architecture. Some works even didn't consider about quality of service (QoS) issue. Provisioning of QoS for multimedia traffic in wireless networks is complicated due to user mobility and limited wireless resources. Next generation system will evolve to those that include dynamic adaptation to traffic and QoS needs. Moreover, mobile terminals (MTs) in wireless environments rely on their limited battery energy for proper operation. Power consumption is a critical design criterion in a wireless network model. A wireless network model that minimizes power consumption is highly desirable. In conventional cellular networks, MTs need to spend larger transmitted power to communicate with BSs when the positions of MTs are far from their own BSs or lie on a cell boundary. The transmitted power has exponential relation with transmission distance [9] [68] [32]. Usually, the exponent is assumed to be equal to 4. However, the total transmitted power of cellular networks can be reduced by using multihopping since messages will be forwarded via relay MTs which split the longer transmission distance between two communicating points into two or more short transmission distances. In this chapter, we will propose QoS constrained minimum-power cellular ad hoc augmented network architecture (QCMP CAHAN) for the next generation wireless networks. The QCMP can find the optimal minimum-power routes under QoS constraints.

The major contribution of the work in this chapter is the proposed QoS constrained minimum-power cellular ad hoc augmented network architecture (QCMP CAHAN) (Figure 2.1). The side effect of such gain is the capacity increase. QCMP CAHAN has a hybrid architecture, in which each MT of CDMA cellular networks has ad

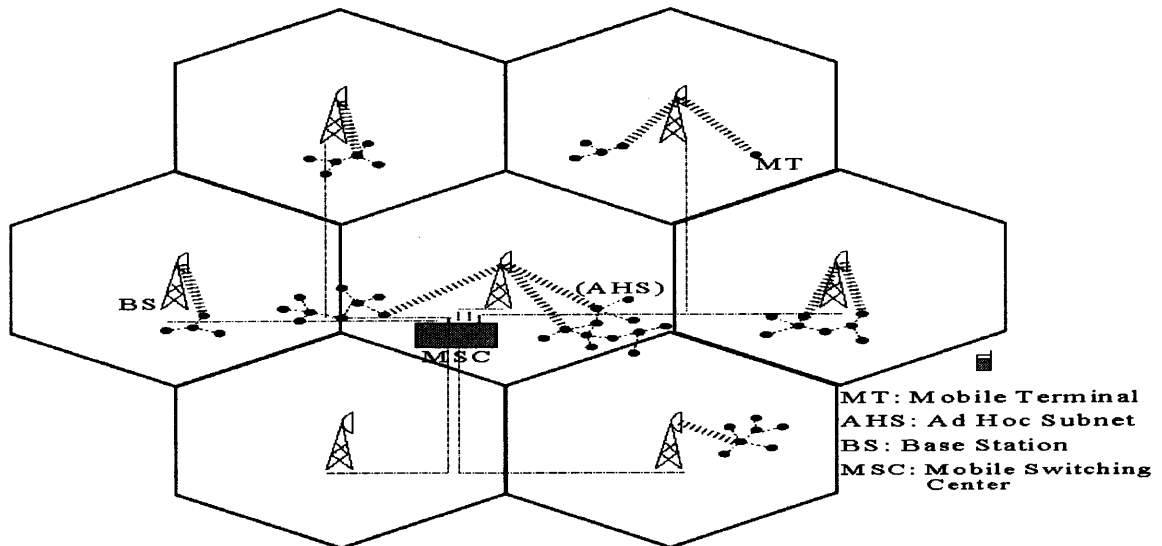


Figure 2.1 QCMP CAHAN architecture.

hoc communication capability. The communication channels for the ad hoc communication system and for the cellular system are separated in frequency. We show that the total energy consumed by the MTs is lower in the case of QCMP CAHAN than in the case of pure cellular networks. As the ad hoc communication range of each MT increases, the total transmitted power in QCMP CAHAN decreases. Typically, the ad hoc communication range of MTs is shorter than the communication range of the BS. It is assumed that there exists a maximum ad hoc communication range, which is determined by the physical power limitations of an MT. In general, in the QCMP CAHAN architecture, energy savings in a denser cell (hot spot cell) will be higher. However, the saving in the total transmitted power does not come free. Due to the increased number of hops involved in information delivery between the source and the destination, the end-to-end delay increases. The number of hops between the BS and the MTs in QCMP CAHAN is a function of the ad hoc communication range of each MT that will be explained later. The maximum end-to-end delay will be limited to a specified tolerable value, and QCMP CAHAN has ability to adapt to various delay constraints in different

regions, intervals, or services. An MT in QCMP CAHAN will not relay any messages when its ad hoc communication range is zero, and if this is the case for all MTs, then QCMP CAHAN reduces to the traditional cellular network, i.e. cellular networks are a special case of QCMP CAHAN. All the schemes described in this work can also be applied to any cellular network.

2.2 Constrained Minimum-Power CAHAN Architecture

2.2.1 Network Architecture & System Model

QCMP CAHAN has a hybrid architecture that comprises the ad hoc network model and the cellular network model.

1) *Ad hoc network model of QCMP CAHAN*: In the ad hoc network model of QCMP CAHAN, peer-to-peer transmissions may involve several router MTs, in which packets are relayed in the same frequency band. For this peer-to-peer model, we use a multirate CDMA protocol with request-to-send/clear-to-send bandwidth reservation mechanism as the medium access technique. The multirate CDMA protocol for the peer-to-peer model can be found in [33], and we will clearly describe it in Section 2.5.2. In CDMA ad hoc system, each MT is assigned one spreading code, and there is a set of spreading codes that may be used by the MTs. Given a set of spreading codes, a spreading code protocol to utilize them is needed. The spreading code protocol is a policy for assigning a spreading code to be used given that a MT has a packet to send, and a policy for monitoring spreading codes given that a MT is idle [34]. The spreading code protocol can be classified as common code, receiver-based code, transmitter-based code, pairwise-based code, and hybrid schemes such as common-transmitter code [34-35]. The

spreading code assignment protocols can be found in [34-35]. However, in the ad hoc network model of QCMP CAHAN, we assume that there are always a sufficient number of spreading codes that can be assigned to MTs such that it will assign distinct spreading codes to different MTs.

To describe the network topology of QCMP CAHAN, we suppose the set of all MTs within the QCMP CAHAN constitute the vertices of a planar graph. R_i denotes the ad hoc communication range of MT i , and R_{max} denotes the maximum ad hoc communication range of MT i , which is determined by the physical power limitations of MT i . The ad hoc communication range of MTs in QCMP CAHAN can be regulated and should be less than their maximum ad hoc communication range R_{max} . The required ad hoc communication range of MTs will be related to the total transmitted power consumption in QCMP CAHAN and the average number of hops from BS to destination MTs. Typically, the ad hoc communication range of MTs is shorter than the communication range of BS (e.g., Bluetooth, whose communication range is between 10 cm to 10 m and can be extended to above 100 m [36], and IEEE 802.11b/IEEE 802.11g, whose maximum communication range is 100m [37]). Therefore, each cell is potentially populated by several ad hoc subnets (AHSs). Each AHS comprises one or more MTs. One AHS may lie on a cell boundary and involve several cells. The topology of AHS can be a tree or a mesh, and it is affected by the ad hoc communication range of each MT in QCMP CAHAN. From a graph theoretic point of view, each BS is a vertex in an AHS subgraph.

2) *Cellular network model of QCMP CAHAN*: For the cellular network model of QCMP CAHAN, two distinct frequency bands between BS and MTs are used separately

to carry the information on the upstream and the downstream. The multirate CDMA is the medium access technique between the BS and the MTs [46]. Since the communication channels for the ad hoc communication system and for the cellular system are separated in frequency, the CDMA spreading code in the ad hoc system and the cellular system can be assigned individually. In the cellular network model of QCMP CAHAN, we also assume that there are always a sufficient number of spreading codes that can be assigned to MTs such that it will assign distinct spreading codes to different MTs.

2.2.2 QCMP CAHAN Cooperation & Routing Strategy

Since the BS in QCMP CAHAN has one-hop connection to each MT, the BS can be regard as the neighbor of each MT. Instead of distributing the routing table into each MT and wasting much control message overhead to propagate the route update information to each MT via peer-to-peer communication, we can implement the routing table only in the BS, which is the one-hop neighbor of each MT. Each MT only needs to update the link-cost information to its one-hop neighbor, i.e. BS. The advantage of this one-hop update mechanism not only saving much control message overhead to forward through all peer-to-peer MTs but also having consistent/reliable up-to-date routing information, i.e., faster response to changes in link cost and network topology. Moreover, since no routing table and complex route computation is needed in each of MT, the implement of QCMP CAHAN will simplify the MT device and save MT battery energy.

The QCMP CAHAN can utilize both centralized and decentralized way for the wireless network construction with the help from a central resource-aware function in BS. The term resource-aware here means that the BS has the knowledge of current

needed transmitted power. The central resource-aware function is implemented into each BS such that the BS has a view on the transmitted power between two MTs, i.e., BS knows the topology of the ad hoc subnets within its individual cell (It will be described later). The MTs and the BS are cooperating in the system, and control packets to exchange control information during the cooperation are needed. To have reliable control information, all the control packets between BS and MTs are sent via cellular system, not the multi-hop peer-to-peer radio link. The sequence of BS and MT operations is:

- 1) *MTs broadcast HELLO packets:* Each MT periodically broadcasts a short HELLO packet that includes its ID and the value of the broadcast power to its neighborhood via common control channel under required ad hoc communication range. The ad hoc communication range of MTs is varied with different broadcast power. The format of HELLO control packet is shown in the following subsection. The update interval is defined as the time interval between update HELLO packet arrivals. The length of the update interval depends on the mobility of MTs, and it will affect a) the accuracy of minimum-power route information gathered. b) the amount of bandwidth and power consumption of control packets. The optimization of the update interval is needed, and it will be discussed in Section 2.5.1.
- 2) *MTs determine the cost of radio link and send the link cost to BS:* The cost of radio link $C_{i,j}$ indicates the needed power from wireless transmitter i to wireless receiver j . The needed power will include transmitted power $P_{i,j}$ required from transmitter i to receiver j and an additional receiver power consumption $P_{j, add}$ of receiver j to devote part of the transceiver to receive and store messages. i.e.,

$$C_{i,j} \equiv P_{i,j} + P_{j, add} . \quad (2.1)$$

After receiving a HELLO packet, a receiver MT j can find the attenuation $\alpha_{i,j}$ according to the received signal strength from neighbor MT i and the broadcast-power information attached in the received HELLO packet. Moreover, the required transmitted power $P_{i,j}$ can be estimated from the attenuation $\alpha_{i,j}$ and the required signal-to-interface ratio (SIR) for data transmission in receiver MT j . The fixed additional receiver power consumption $P_{j, add}$ of receiver j is known by receiver j , and it depends on the transceiver hardware of receiver j . After calculating all one-direction link costs $C_{k,j}$ ($k \in \text{neighbors of } j$), receiver MT j will send neighbor-update (NEUP) packet to central BS to update the neighbor and link cost information. To have reliable link cost and neighbor information, the NEUP control packet will be transmitted directly via one-hop cellular radio link. The isolated MTs don't need to send NEUP packet. Each NEUP control packet has the information of neighbor ID and link cost. All the link cost information will be sent to the BS such that each BS has a view on the "two-direction" link cost information of the AHS within its individual cell. However, the BS only can get a part of link cost information of the AHS which lies on the cell boundary. Another part of link cost information of the AHS on cell boundary must be gotten from the neighbor BS. Getting the link cost information of AHS from its neighbor BS will be processed only when there is a source/destination MT in the AHS on cell boundary. MSC can help the BSs to get the link-cost information of the AHS on cell boundary, since it has a routing table which stores MT ID, ID of the cell

which the MT lies on, and best-relay BS ID (It will be described later). The cell ID of a neighbor MT on cell boundary will indicate which cell has another part of link cost information of the AHS on cell boundary.

- 3) *BS finds optimal routes and updates the optimal route information:* After getting link-cost information from its neighbor BS, each BS knows the topology of the AHSs which include the AHSs on cell boundary and the AHSs within its cell. The BS has a topology table, which stores MT IDs, neighbor IDs, and link costs (A MT's neighbors include the neighbor MTs and its one-hop BS). Therefore, the BS can find the optimal route between any two wireless devices in the same/different AHS based on the information it has. The way to search the optimal route will be discussed in Section 2.3. The BS which lies in the optimal route is called the best-relay BS. When all the MTs of an AHS are within a cell, their own BS will be the best-relay BS since it is the only one BS which could lie in the optimal route. However, when the AHS lies on cell boundary and covers several cells, we have to decide which neighbor BS will be in the optimal route. Therefore, to the MTs on cell boundary, the best-relay BS may be not their own BS (It depends on which neighbor BS is in the optimal route). After searching the optimal route, a BS will find which neighbor BS is the best-relay BS for the MT on cell boundary to transmit/receive the data packet. The optimal route searching will be processed only in one BS which a source/destination MT belongs to. The BS will send optimal route information to the best-relay BS only if the BS itself is not the best-relay BS and there is a MT on cell boundary receiving data packet from BS. Moreover, updating best-relay BS information to the MSC is needed only when a

MT is receiving a downlink message from the MSC. In upstream transmission, the source MT will get the route information (a sequence of relay MT) only from its own BS; the route information is carried by route-update (RUP) packet, which is sent from the BS via cellular system. To route to the destination, each original data packet is encapsulated by preceding it with route information (a sequence of relay MT). The encapsulation is done by the source MT in upstream transmission or by the BS in downstream transmission. In upstream transmission, the BS will decapsulate the data packet and then forwards it to its ultimate destination like pure cellular networks. Since isolated MTs have directly connection with BS, no encapsulation/decapsulation, RUP packet, and NEUP packet is needed for the isolated MTs, i.e., the isolated MTs will only need to send out HELLO packet. BS knows the number of MTs in its cell since it has MT ID list. When there is only one or two MTs in a cell (i.e., very low network density) and each MT is an isolated MT for a certain time (even under maximum ad hoc communication range), the BS will broadcast a message to the isolated MTs to rest their ad hoc communication system to avoid sending the HELLO packet, and the QCMP CAHAN will reduce to pure cellular networks. Normally, since BS already has the route information, there is no RUP packet needed in downlink transmission. Once a link breakage (link fail) happen during an update interval, the BS will send an updated RUP packet to the source MT which has a traffic flow through the broken link. Another update RUP is sent to the “link-breakage” router MT which has a connection with the broken link. Therefore, all the packets which stay

in the “link-breakage” router MT won’t be lost and can be redirected to the destination MT via the new route.

- 4) *Regulating end-to-end hop count to meet QoS constraint*: The data packets for upstream and downstream transmissions will be relayed through the optimal routes. However, to meet end-to-end QoS requirement (delay/throughput) or avoid the traffic congestion, the end-to-end hop count should be constrained. In normal operation, the ad hoc communication range is increased and regulated by BS until end-to-end hop count reach its maximum tolerable value or the ad hoc communication range reach its physical maximum value. The BS in upstream transmission or a destination MT in downstream transmission can sense the data packet delay and throughput. When end-to-end QoS requirement doesn’t be satisfied, the BS can do either way below to find a new constrained optimal route:
- a) decrease the ad hoc communication range of MTs. b) run a k-hop constrained Bellman-Ford algorithm with less number of hop constraints. The k-hop constrained Bellman-Ford algorithm for searching optimal route will be described clearly in Section 2.3.

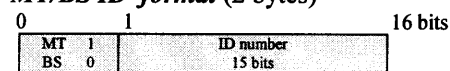
CAHAN Control Packet Format¹

1) Control packet for system maintenance:

A) HELLO packet (7 bytes) = {HELLO transmitter MT ID, broadcast ID, HELLO message type, broadcast power}



MT/BS ID format (2 bytes)



HELLO broadcast ID is 1111111111111111

¹ The physical layer entities such as synchronization and error detection fields are excluded.

B) NEUP (≥ 10 bytes) = {transmitter MT ID, receiver BS ID, NEUP message type, # of neighbors, list of neighbor ID and its power cost}

transmitter MT ID 2 bytes	receiver BS ID 2 bytes	NEUP message type 1 byte	# of neighbors 1 byte	neighbor ID [I] 2 bytes	power cost [I] 2 bytes	neighbor ID [II]
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C) RUP (≥ 6 bytes) = {transmitter BS ID, receiver MT ID, RUP message type, # of relay MTs, assigned traffic data rate, list of relay MT IDs}

transmitter BS ID 2 bytes	receiver MT ID 2 bytes	RUP message type 1 byte	# of relay MTs 1 byte	assigned traffic data rate 2 bytes	relay MT ID [I] 2 bytes	relay MT ID [II]
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2) Control packet for peer-to-peer data transmission²: [33]

RTS control packet is used by a transmitter MT to initiate a session with another MT. CTS control packet is issued by the receiver MT of the RTS packet if it can support the QoS requested. ESR control packet is used by the transmitter MT to signify the end of a session. ESA control packet is sent by the receiver MT in response to the ESR packet.

Peer-to-peer session setup

A) RTS (12 bytes) = {transmitter MT ID, receiver MT ID, RTS message type, minimum SIR requirement, minimum transmission data rate (kbps), maximum transmission power, size of packet train (bytes)}

transmitter ID 2 bytes	receiver ID 2 bytes	RTS message type 1 byte	minimum SIR requirement 1 byte	minimum data rate 2 bytes	maximum transmission power 2 bytes	size of packet train 2 bytes
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B) CTS (13 bytes) = {receiver MT ID, transmitter MT ID, CTS message type, minimum SIR requirement, minimum transmission data rate, allocated transmitted power, allocated data rate, estimated duration (0.01sec)}

receiver ID 2 bytes	transmitter ID 2 bytes	CTS message type 1 byte	minimum SIR requirement 1 byte	minimum data rate 2 bytes	allocated transmitted power 2 bytes	allocated data rate 2 bytes	duration 1 byte
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Peer-to-peer session end

C) ESR (5 bytes) = {transmitter MT ID, receiver MT ID, ESR message type}

transmitter MT ID 2 bytes	receiver MT ID 2 bytes	ESR message type 1 byte
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D) ESA (6 bytes) = {receiver MT ID, transmitter MT ID, ESA message type, negative acknowledgement NACK}

receiver MT ID 2 bytes	transmitter MT ID 2 bytes	ESA message type 1 byte	NACK 1 byte
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2.2.3 Correctness of System Operation

To show the QCMP CAHAN system can operate completely correctly, we describe the cooperation processes for MT, BS, and MSC in QCMP CAHAN for all possible scenarios below, given two MTs are communicating each other.

Case 1. two MTs in the same AHS within a cell: From a graph theoretic point of view,

² A multirate CDMA protocol with RTS/CTS bandwidth reservation mechanism is the medium access technique. Control messages are broadcasted on common control channel. The data session negotiates on a per data packet basis.

each BS is a vertex in an AHS subgraph. The BS can find the optimal route between two MTs in the same AHS and send the RUP packet to the source MT. Depending on the availability of radio resource, since the BS could be selected be a router in the optimal route, the pure peer-to-peer connection between two MTs in the AHS subgraph may not be the only one choice.

Case 2. two MTs in the same AHS which lies on cell boundary (Two MTs may connect with different/same BS/MS): The source/destination MT's own BS gets a part of link cost information of the AHS subgraph on cell boundary from its neighbor BS. The part of link cost information not only includes the link cost between two neighbor MTs but also the link cost between the MTs and their own BSs. Once the BS receives all the link cost information, a new subgraph is constructed, which consists of the MTs (in the AHS), their own BSs, a MSC, and all the links between them. However, in the new subgraph, due to the limitation of the wireless resource, the radio link cost (bandwidth/transmitted power) should be more important than the wire link cost between two BSs. After searching the optimal route, the source/destination MT's own BS finds which neighbor BS is the best-relay BS for the MTs to transmit/receive the data packet.

A) When the MT is a source MT: The BS of the source MT will send the RUP packet to the source MT. The optimal route may include peer-to-peer route and uplink-downlink route.

B) When the MT is a destination MT and receiving packets from BS: If the BS itself is not the best-relay BS, the BS will send optimal route information to the best-relay BS. Updating the best-relay BS information to MSC is needed only when the MT is receiving a downlink message from the MSC.

Case 3. two nodes in the different AHS within a cell: Since a BS is regarded as a vertex which belongs to each AHS subgraph within a cell, the BS has to find two optimal routes. One is the optimal route from source MT to the BS, and the other is the optimal route from the BS to the destination MT. BS will send the RUP packet to the source MT.

Case 4. two nodes in the different AHS and each AHS lies within different cell (Two MTs may connect with different MSC): The cooperation between BS and MT will be similar as Case 3. Each BS of the source MT (destination MT) has to find an optimal route between the BS and the MT. However, a connection between two different BSs is needed. MSC can handle the traffic flow between these two BSs and switch the packets to the destination BS since it has a routing table (including MT ID, ID of the cell which the MT lies on, and best-relay BS ID).

Case 5. two nodes in the different AHS and each AHS lies on different cell boundary: The cooperation between BS and MT will be the same as Case 2. Only different is that there is no pure peer-to-peer connection between the two AHS subgraphs.

2.2.4 System Scalability, Reliability, and Robustness

System scalability is used to explore the performance complexity, i.e., the effect of network size on system performance including packet traffic load, total overhead, and memory requirements. The global amount (bytes) of memory needed in all network elements will be an indication of the overall complexity. Moreover, because of the multihop nature of ad hoc networks, the scalability of QCMP CAHAN is directly related to the routing protocol. A routing protocol is said to be scalable with respect to the network size if and only if, as the network size increases, the total overhead induced by such protocol does not increase faster than the network's minimum traffic load, which is

the minimum amount of bandwidth required to forward packets over the minimum-hop paths [74]. Therefore, QCMP CAHAN can be made more scalable by reducing the overhead and memory requirements for the system.

The proposed QCMP CAHAN architecture has good scalability, even for large user populations, mainly because of:

- 1) *The topology table in BS improves the scalability of QCMP CAHAN:* The whole topology of network in QCMP CAHAN is distributed into each BS, and the topology table in each BS will only store the topology (link cost) information of the AHSs within an individual cell. Each MT only needs to update the link cost information to its one-hop BS via cellular system such that it will avoid sending most control overheads through the whole QCMP CAHAN and propagating the control overheads to every MT via peer-to-peer communication. Therefore, the reduction of the overhead in QCMP CAHAN can be achieved by limiting the update information only to BS and limiting the time between successive update information dissemination. Moreover, since the neighbor information is stored only in the BSs instead of all the MTs, the total amount of memory needed in QCMP CAHAN is also less.
- 2) *The use of routing table in MSC also increases the scalability of QCMP CAHAN:* The routing table in MSC only stores MT ID, the ID of the cell which a MT lies on, and best-relay BS ID. Once a new MT joins the QCMP CAHAN, only one-row message is needed to update the MT ID, the cell ID and the best-relay BS ID. The length of update message is small, constant, and not related to the total number of MTs in QCMP CAHAN. Therefore, the total memory occupation of

the routing table in the MSC of QCMP CAHAN is small and only linear with the total number of MTs N in QCMP CAHAN, i.e., the complexity of the routing table in the MSC is only $O(N)$.

- 3) *The end-to-end hop-count-constrained scheme scales well in large user populations:* By decreasing the communication range of the MTs to meet end-to-end hop count requirement, a big AHS in QCMP CAHAN can be split into several small AHSs. Therefore, the size of the AHS in QCMP CAHAN can be reduced, and the traffic flows in the AHS will be limited. That will decrease the performance complexity of the system.
- 4) *Route optimization reduces the resource demands in QCMP CAHAN:* The route optimization in QCMP CAHAN can reduce the resource demands and avoid any possible performance bottleneck in high network density. The overhead of the routing protocol in QCMP CAHAN is not heavily influenced by network size and mobility. This translates to good scalability for large and dynamic QCMP CAHAN.
- 5) *Total overhead induced by QCMP CAHAN does not increase faster than total traffic load:* The control overhead, as a fraction of the total traffic, is small, and the control channel bandwidth consumption of the control packet in QCMP CAHAN is much less (Section 2.7). The reduction of the overhead in QCMP CAHAN is achieved. As the total number of MTs in QCMP CAHAN increasing, the total overhead induced does not increase faster than the total number of data message received in the destinations. These observations indicate a highly scalable [74].

System reliability is another important issue in wireless network. Offering reliable delivery of data to fast moving MTs adds substantial complexity to the communication in wireless network. System reliability is a key factor which determines QoS. In wireless network, the individual nodes present a high degree of unreliability that gives rise to frequent temporary failures. These temporary failures are typically caused by the fact that a link breakage happen (due to mobility) or a node failure (due to battery energy depletion). Reliability of a network can be defined as the probability that two nodes in every node-pair in the system can communicate with each other [83], i.e., the probability that at least 1 path exists between each pair of nodes in this network [75-76]. In QCMP CAHAN, a MT can dynamically select to access a cellular radio link or ad hoc radio link depending on the availability of the wireless resources, such that the probability that at least 1 path exists between source and destination in QCMP CAHAN will be the summation of the probability of at least 1 path exists in cellular system and the probability of at least 1 path exists in ad hoc system. Therefore, the probability that at least 1 path exists between source and destination in QCMP CAHAN is greater than that in the pure cellular networks. QCMP CAHAN has higher system reliability, as comparing with the cellular networks.

System robustness is also considered in QCMP CAHAN design. QCMP CAHAN system is robust enough to accommodate different kinds of packet losses due to link errors, connection re-routing, and network congestion. A multipath routing scheme is an optional technique and a good strategy in QCMP CAHAN to increase the system robustness to failures [81-82]. In the multipath routing scheme, multiple disjoint or partially disjoint routes are used to convey information from source to destination. The

basic idea behind multipath routing is fault-tolerance through redundancy. However, to save the radio resource, the multipath routing scheme is used only when certain QoS requirement (packet loss rate) of QCMP CAHAN is not satisfied. In QCMP CAHAN, a BS is regarded as a node which belongs to each AHS within its cell. Each BS has the topology of the AHSs and can easily find multiple routes between any two nodes in an AHS (Section 2.3). As comparing with other multipath routing techniques in ad hoc network, the advantage of our multipath routing technique is that it only need to make a search on the topology table in a BS and doesn't really send any query control message to flood the network to discovery the multiple routes, i.e., no extra control overhead needed. In the multipath routing technique, the data packets will be flowed simultaneously along the multiple routes to against packet losses and increase the system robustness.

2.3 QoS Constrained Minimum-Power Considerations

2.3.1 Minimum Power Consideration

Mobile devices in wireless environments rely on their limited battery energy for proper operation. Finding the optimal minimum-power routes in a wireless network model is highly desirable. Moreover, the heterogeneous wireless applications are emerging, and some wireless applications are delay sensitive. However, the radio resource (power and bandwidth) is scarce in a wireless network. Therefore, the QCMP CAHAN should support heterogeneous applications with minimum power consumption under different QoS requirements.

2.3.2 QoS Constrained Problem Formulation & Approach

Due to its direct connection with each MT, the BS in QCMP CAHAN can take advantage of fast and efficient collection of the transmitted-power information of the radio links. As mentioned before, the QCMP CAHAN can utilize both centralized and decentralized way for the wireless network construction with the help from the central power-aware function in BS. The term power-aware here means that the BS has the knowledge of currently exact transmitted power between two MTs within its cell. The required transmitted power in each direction of a radio link will present the different link cost. To describe the network topology of QCMP CAHAN, we suppose the set of all MTs and BSs in the QCMP CAHAN constitute the vertices of a directed graph (digraph) $G = (V, E)$ where V denotes the vertex set of G and E denotes the edge set of G . An MT that lies within the ad-hoc communication range of another MT is referred to as its neighbor. A directed graph is strongly connected if every two vertices are reachable from each other. Since each MT has bidirectional link with BS via cellular system, the directed graph G is strongly connected. Every two nodes in the directed graph G are reachable from each other. The minimum-power route between two nodes in the graph G can be found by using a shortest path algorithm. However, to support heterogeneous wireless applications with various QoS requirements, the shortest path algorithm should run on a QoS-constrained graph.

Metric 1- Metrics of QoS Constrained Problem: Given a directed graph $G = (V, E)$ where V denotes the vertex set of G and E denotes the edge set of G . A *path* of length h (hop count h) from a vertex $s \in V$ to a vertex $d \in V$ is a finite sequence of vertices $\langle v_0, v_1, v_2, \dots, v_h \rangle$, such that $s = v_0$, $d = v_h$, and $(v_{i-1}, v_i) \in E$ for $i = 1, 2, \dots, h$. A *path* is *simple* if all

vertices in the path are distinct, i.e., for all $0 \leq m < n \leq h$, $v_m \neq v_n$. Suppose each edge $(v_{i-1}, v_i) \in E$ has a weight(cost) $c(v_{i-1}, v_i) \geq 0$. Corresponding to a path $\zeta = \langle v_0, v_1, v_2, \dots, v_h \rangle$, there is a path weight $C(\zeta)$, which is a nondecreasing function of the weights of the links along the path. In the QoS constrained shortest path problem, the weight of path ζ is the sum of the weights of its constituent edges:

$$C(\zeta) = \sum_{i=1}^h c(v_{i-1}, v_i). \quad (2.2)$$

The object of metric 1 is to minimize $C(\zeta)$. Given edge weights c , source node s , and destination node d , an optimal path (shortest path) from s to d is then defined as any path ζ with minimum weight $C_{\min}(s, d)$. The minimum weight $C_{\min}(s, d)$ is

$$C_{\min}(s, d) = \begin{cases} \min\{C(\zeta)\} & \text{if there is a path } \zeta \text{ from node } s \text{ to node } d \\ \infty & \text{otherwise} \end{cases} \quad (2.3)$$

Moreover, the QoS constraint can be expressed in terms of several important parameters: packet delay, minimum bandwidth (throughput) requirement, and maximum packet loss/error rate [33]. In QCMP CAHAN, the end-to-end packet delay is affected by the hop count between BS and MTs. The minimum bandwidth requirement of service will affect the selection of the routes due to the limitation of radio link bandwidth. The maximum packet error rate (PER) is related to the signal-to-interface ratio (SIR) requirement in a power allocation scheme. In power-aware QCMP CAHAN, the power consumption from node v_{i-1} to node v_i is selected to be the weight $c(v_{i-1}, v_i)$ of each edge $(v_{i-1}, v_i) \in E$. Therefore, depending on the constraint, the QoS constrained problems in QCMP CAHAN will include:

1) *Bandwidth Constrained Problem*: Assuming the multiple routs exist between a source and a destination, the bandwidth constrained problem can be handled by splitting the traffic of the source MT. Given a maximum hop count requirement H for all possible routes from source to destination and a minimum data rate requirement r_{QoS} for a QoS service, i.e.,

$$\sum_{\zeta \in R(s)} x_{\zeta} = r_s \geq r_{QoS}, 1 \leq h_{\zeta} \leq H, \zeta = \langle v_0, v_1, v_2, \dots, v_h \rangle, s = v_0, d = v_h.$$

where $R(s)$ is the set of routes starting at source s , x_{ζ} is the flow (traffic rate) on route ζ , r_s is the traffic rate that is associated with source s and is split by s on its route set $R(s)$, h_{ζ} is the hop count of the route ζ .

Consider a network with a link set (edge set) E , and let B_l be the bandwidth constraint of radio link l , $l \in E$. Let $B = (B_l, l \in E)$ and $X = (x_{\zeta}, \zeta \in R(s))$. Set $A_{l,\zeta} = 1$ if radio link $l \in \zeta$, so that link l lies on route ζ , and set $A_{l,\zeta} = 0$ otherwise. This defines a matrix $A = (A_{l,\zeta}, l \in E, \zeta \in R(s))$. Let R_l is the set of routes through radio link l . Under the multiple route condition, the bandwidth constrained problem can be described as the following nonlinear programming.

$$\text{Minimize } C(\zeta, x_{\zeta}) = \sum_{\zeta \in R(s)} \sum_{i=1}^{h_{\zeta}} c_{\zeta}(v_{i-1}, v_i) \cdot l_{\zeta}(x_{\zeta}) = \sum_{\zeta \in R(s)} l_{\zeta}(x_{\zeta}) \sum_{i=1}^{h_{\zeta}} c_{\zeta}(v_{i-1}, v_i).$$

$$\text{Subject to } AX \leq B \quad (\text{i.e., } \sum_{\zeta \in R_l} x_{\zeta} \leq B_l, l \in E)$$

$$x_{\zeta} \geq 0 \tag{2.4}$$

where $C(\zeta, x_{\zeta})$ is total radio resource cost on route set $R(s)$, $c_{\zeta}(v_{i-1}, v_i)$ is the power consumption from node v_{i-1} to node v_i on route ζ , $l_{\zeta}(x_{\zeta})$ is the bandwidth-cost function

for x_ζ on route ζ . $l_\zeta(x_\zeta)$ relates to the needed bandwidth consumption for a radio link. Assume that the $l_\zeta(x_\zeta)$ is an increasing, strictly convex and continuously differentiable function of x_ζ over the range $x_\zeta \geq 0$.

2) *Hop-Count Constrained Shortest Path Problem*: For a given source node $s \in V$ and maximum hop count H , find, for each hop count value h , $h \leq H$, and destination node $d \in V$, a hop constrained shortest path between s and d . i.e.,

$$\begin{aligned} \text{Minimize } C(\zeta) &= \sum_{i=1}^h c(v_{i-1}, v_i). \quad \zeta = \langle v_0, v_1, v_2, \dots, v_h \rangle, \quad s = v_0, \quad d = v_h \\ \text{Subject to } 1 \leq h \leq H, \quad &\forall (v_{i-1}, v_i) \in E \end{aligned} \quad (2.5)$$

3) *SIR Constrained Shortest Path Problem*: For a given source node $s \in V$ and the minimum SIR constraints $\gamma_{i-1,i}$ from node v_{i-1} to node v_i , find, for each destination node $d \in V$, a SIR constrained shortest path between s and d . i.e.,

$$\begin{aligned} \text{Minimize } C(\zeta) &= \sum_{i=1}^h c(v_{i-1}, v_i). \quad \zeta = \langle v_0, v_1, v_2, \dots, v_h \rangle, \quad s = v_0, \quad d = v_h \\ \text{Subject to } \left. \frac{E_b}{I_0} \right|_{i-1,i} &\geq \gamma_{i-1,i} \quad \forall (v_{i-1}, v_i) \in E \end{aligned} \quad (2.6)$$

where E_b denotes bit energy from v_{i-1} to v_i and I_0 denotes total interference density from v_{i-1} to v_i .

The QoS constrained problems in QCMP CAHAN have been described above. Here, we propose the approaches for these QoS constrained problems. The description of the approaches is as follows:

1) *Bandwidth Constraint Approach*

As mention before, all possible routes ζ (under maximum hop count) from source to

destination in QCMP CAHAN can be found by using a multiple-route searching scheme on the network topology table of the BS. No any query control message is sent to flood the network to discovery the multiple routes. The multiple-route searching scheme will seek routes via bread-first-search algorithm (i.e., hop by hop) from source to destination. Differently, to allow having partially disjointed routes, a node can be allowed visited more than once. However, during the searching, the route which has a routing loop will be eliminated, i.e., we only traverse the routes which have no routing loop. The multiple-route searching scheme will be processed until the disjoint (or partially disjoint) routes reach the destination or the maximum hop count requirement.

We consider the bandwidth-cost function $l_\zeta(x_\zeta)$ for the generic route ζ as [77]

$$l_\zeta(x_\zeta) = \log(1 + x_\zeta) \quad (2.7)$$

Observe that $l_\zeta(x_\zeta)$ increases as the data rate x_ζ increases; the log function is used in the expression of the link utility because it ensures proportional fairness.

The Lagrangian function $L(x, \lambda)$ for the bandwidth constrained problem is

$$\begin{aligned} L(x, \lambda) &= \sum_{\zeta \in R(s)} l_\zeta(x_\zeta) \sum_{i=1}^{h_\zeta} c_\zeta(v_{i-1}, v_i) + \lambda^T (B - AX) \\ &= \sum_{\zeta \in R(s)} \log(1 + x_\zeta) \sum_{i=1}^{h_\zeta} c_\zeta(v_{i-1}, v_i) + \lambda^T (B - AX). \end{aligned} \quad (2.8)$$

λ is a vector of Lagrangian multipliers (i.e., shadow prices).

The optimal solution of the inequality constrained problem in (2.4) must satisfy the first-order Karush-Kuhn-Tucker optimality conditions, i.e.,

$$\nabla_x L(x, \lambda) = 0 \quad \& \quad \lambda^T (B - AX) = 0. \quad (2.9)$$

Therefore,

$$\begin{aligned} \frac{\partial L(x, \lambda)}{\partial x_\zeta} &= \frac{\sum_{i=1}^{h_\zeta} c_\zeta(v_{i-1}, v_i)}{1 + x_\zeta} - \sum_{i \in \zeta} \lambda_i \\ &= 0 \end{aligned} \quad (2.10)$$

and so the unique optimum solution to the inequality constrained problem is given by

$$x_\zeta = \frac{\sum_{i=1}^{h_\zeta} c_\zeta(v_{i-1}, v_i)}{\sum_{i \in \zeta} \lambda_i} - 1 \quad (2.11)$$

under the complementary slackness condition $\lambda^T(B - AX) = 0$, $\lambda \geq 0$.

Here, we would like to introduce another approach, so called penalty method, to solve the inequality constrained problem in (2.4). The penalty method is procedure for approximating constrained optimization problem by unconstrained problem. By using an exact penalty function, the penalty method offers a simple straightforward method for handling constrained problems. A penalty function is said to be exact if a constrained nonlinear programming problem can be solved by a single minimization of an unconstrained problem [77-78]. An scalar penalty function $\varphi(t)$ for the inequality constrained problem in (2.4) given by

$$\varphi(t) = \begin{cases} e^{\beta t} - 1, & t \geq 0 \\ 0, & t < 0. \end{cases} \quad (2.12)$$

Where β is any sufficiently large value [77]. In [77], it shows that $\varphi(t)$ is an exact penalty function and satisfies the following assumptions:

- A) $\varphi(t)$ is convex
- B) $\varphi(t) = 0 \quad \forall t \leq 0$

$$C) \varphi(t) > 0 \quad \forall t > 0.$$

By using the exact penalty function $\varphi(t)$, we can replace the constrained optimization problem in (2.4) by the following unconstrained optimization problem:

$$\text{Minimize } Q(\zeta, x_\zeta) = C(\zeta, x_\zeta) + \sum_{l \in E} \varphi\left(\sum_{\zeta \in R_l} x_\zeta - B_l\right) + \sum_{\zeta \in R(s)} \varphi(-x_\zeta). \quad (2.13)$$

Where $Q(\zeta, x_\zeta)$ is the object of the unconstrained optimization problem (2.13).

$$\begin{aligned} Q(\zeta, x_\zeta) &= C(\zeta, x_\zeta) + \sum_{l \in E} \varphi\left(\sum_{\zeta \in R_l} x_\zeta - B_l\right) + \sum_{\zeta \in R(s)} \varphi(-x_\zeta) \\ &= \sum_{\zeta \in R(s)} l_\zeta(x_\zeta) \sum_{i=1}^{h_\zeta} c_\zeta(v_{i-1}, v_i) + \sum_{l \in E} \varphi\left(\sum_{\zeta \in R_l} x_\zeta - B_l\right) + \sum_{\zeta \in R(s)} \varphi(-x_\zeta) \\ &= \sum_{\zeta \in R(s)} \log(1 + x_\zeta) \sum_{i=1}^{h_\zeta} c_\zeta(v_{i-1}, v_i) + \sum_{l \in E} \varphi\left(\sum_{\zeta \in R_l} x_\zeta - B_l\right) + \sum_{\zeta \in R(s)} \varphi(-x_\zeta) \end{aligned} \quad (2.14)$$

Thus, by solving the unconstrained problem given by problem (2.13), we can obtain a solution to problem (2.4). If $Q(\zeta, x_\zeta)$ in problem (2.13) is convex and the set X is open, then $\nabla Q(\zeta, x_\zeta) = 0$ is a necessary and sufficient condition for a vector $x^* \in X$ to be a global minimum of $Q(\zeta, x_\zeta)$ over X [79]. Any gradient decent method (Newton's method or steepest decent method) can be used to solve the problem in (2.13) [79]. Most of the gradient decent methods can be specified in the iteration form

$$x_{\zeta, k+1} = x_{\zeta, k} - \alpha_k D_k \nabla Q(\zeta, x_{\zeta, k}). \quad (2.15)$$

where α_k is step size at k iteration and is chosen to be positive. D_k is a positive definite symmetric matrix and depends on the selected gradient decent method:

$$D_k = \begin{cases} I_{n \times n}, & \text{Steepest decent method} \\ (\nabla^2 Q(\zeta, x_{\zeta, k}))^{-1}, & \text{Newton's method.} \end{cases} \quad (2.16)$$

The iteration of the searching will be processed until $\nabla Q(\zeta, x_{\zeta, k}) = 0$. When

$\nabla Q(\zeta, x_{\zeta,k}) = 0$, $x_{\zeta,k+1}$ will be equal to $x_{\zeta,k}$, i.e., the generated sequence $\{x_{\zeta,k}\}$ converges to an optimal value.

2) Hop-Count Constraint Minimum Power Approach

A) *Proximity limitation shortest path*: From a graph theoretic point of view, the BS in QCMP CAHAN is regarded as a vertex which belongs to each AHS subgraph within its cell, and the BS has a connection with each MT within its cell. The network topology of the QCMP CAHAN is affected by the ad hoc communication range of MTs. In QCMP CAHAN, the number of minimum-power hops $h_{p_{\min}}$ between BS and MT is a monotonically nondecreasing function of the ad hoc communication range of MT, i.e.,

$$h_{p_{\min}}(R_i) \leq h_{p_{\min}}(R_i''), \quad \text{if } R_i \leq R_i'' \quad \forall i \in s \quad (2.17)$$

Where R_i denotes the ad hoc communication range of MT i . s denotes the set of MTs being served from the BS.

QCMP CAHAN can regulate the ad hoc communication range R of MTs to meet the hop-count constraint H . After regulating the ad hoc communication range, a H hop constrained minimum-power route can be found by using any shortest path algorithm such as Dijkstra algorithm or Bellman-Ford algorithm [66]. The problem of finding shortest paths from a given origin node to all other nodes (Ex. downlink from a BS to MTs) is equivalent to the problem of finding all shortest paths to a given destination node (Ex. uplink from MTs to a BS). The Dijkstra algorithm requires that all link costs are nonnegative. In the worst case its computational complexity is $O(N^2)$, comparing with the worst-case estimate $O(N^3)$ of the Bellman-Ford algorithm. The worst-case computational requirements of the Dijkstra algorithm are considerably less than those of

the Bellman-Ford algorithm. Therefore, the Dijkstra algorithm is more suitable for dense networks, as compared with Bellman-Ford algorithm. The general idea of the Dijkstra algorithm is to find the shortest paths in order of increasing link cost. The Dijkstra algorithm maintains a set S of vertices whose final minimum link cost from the destination. In each step, the Dijkstra algorithm always chooses the closest (least-cost) vertex $j \notin S$ to inset into set S and use it to attempt to improve other nodes' cost. i.e., for all $j \notin S$

$$C_j \leftarrow \min[C_j, d_{ji} + C_i] \quad (2.18)$$

At the q^{th} step we have the set S of “the q least-cost nodes” to destination as well as the least cost C_i from each node $i \in S$ to destination.

Let $P_k^{h=l}$ denote the needed power of the k -th link in minimum-power route $h_{p_{\min}} = l$ between BS and MT i in QCMP CAHAN. Given a maximum hop count requirement H for all possible routes between MT i and BS. When ad hoc communication range R_i of MT i is 0, $h_{p_{\min}}$ will be equal to 1, and the one-hop power between MT i and BS will be $P_1^{h=1}$. As the R_i is increased, more neighbors of MT i can be found, and the $h_{p_{\min}}$ is increased. The needed power with the various $h_{p_{\min}}$ is shown below:

$$\begin{aligned} P_1^{h=1} & \quad [when \ h_{p_{\min}} = 1] \\ \geq P_1^{h=2} + P_2^{h=2} & = \sum_{l=1}^2 P_l^{h=2} \quad [when \ h_{p_{\min}} = 2] \\ \geq P_1^{h=3} + P_2^{h=3} + P_3^{h=3} & = \sum_{l=1}^3 P_l^{h=3} \quad [when \ h_{p_{\min}} = 3] \\ \geq \dots & \\ \geq P_1^{h=H} + P_2^{h=H} + P_3^{h=H} + P_4^{h=H} \dots + P_H^{h=H} & = \sum_{l=1}^H P_l^{h=H} \quad [when \ h_{p_{\min}} = H] \end{aligned}$$

Generalizing the statement above and the inequality in (2.17), we can get

$$P_1^{h=1} \geq \sum_{l=1}^{h_{p_{\min}}(R_i)} P_l^{h=h_{p_{\min}}(R_i)} \geq \sum_{l=1}^{h_{p_{\min}}(R_i'')} P_l^{h=h_{p_{\min}}(R_i'')} \geq \sum_{l=1}^H P_l^{h=H} \quad (2.19)$$

Obviously, the relation of ad hoc communication range R_i , maximum number of

minimum-power hops $h_{p_{\min}}(R_i)$, and needed power $\sum_{l=1}^{h_{p_{\min}}(R_i)} P_l^{h=h_{p_{\min}}(R_i)}$ is

$$R_i \uparrow \quad \text{then} \quad \Rightarrow \quad h_{p_{\min}}(R_i) \uparrow \quad \text{then} \quad \Rightarrow \quad \sum_{l=1}^{h_{p_{\min}}(R_i)} P_l^{h=h_{p_{\min}}(R_i)} \downarrow$$

B) *K-hop limitation shortest path*: Unlike the Dijkstra algorithm, at its h th iteration, the Bellman-Ford algorithm identifies the optimal path between a given destination and other nodes, among paths of “at most h hops”. Therefore, the QCMP CAHAN can take the advantage of the k -hop constrained Bellman-Ford algorithm to find the k -hop constrained minimum power routes.

- i) *Basic concept of Bellman-Ford algorithm*: A shortest path from a given node i to destination, subject to the constraint that the path contains at most k hops and goes through destination θ only once, is referred to as a k -hop constrained shortest path (hop count $h \leq k$) and its cost is denoted by C_i^h . Assume that all cycles not containing destination θ have nonnegative cost. C_i^h can be generated by the iteration

$$C_i^{h+1} = \min_j [C_{i,j} + C_j^h] \quad \text{for all } i \neq \theta \quad (2.20)$$

- ii) *The property of the Bellman-Ford algorithm* [66]: Consider the Bellman-Ford algorithm in (2.20) with the initial condition $C_i^0 = \infty$ for all $i \neq \theta$. Then:

- a) The C_i^h generated by the algorithm are equal to the k-hop constrained shortest path (hop count $h \leq k$) from node i to destination θ .
- b) The algorithm terminates after a finite number of iteration if and only if all cycles not containing destination θ have nonnegative cost. Furthermore, if the algorithm terminates, it does so after at most $h \leq \aleph$ iterations (\aleph the total number of nodes), and at termination, C_i^h is the shortest path cost from node i to destination θ .

3) SIR Constraint Minimum Power Approach

A) *Link-cost limitation shortest path*: Each maximum packet error rate (PER) from node v_{i-1} to node v_i is associated with a signal-to-interference ratio (SIR) constraints $\gamma_{i-1,j}$. Let ζ denote a path from v_0 to v_h . Consider the SIR constrained shortest path problem in (2.6), i.e.,

$$\text{Minimize } C(\zeta) = \sum_{i=1}^h c(v_{i-1}, v_i).$$

$$\text{Subject to } \left. \frac{E_b}{I_0} \right|_{i-1,j} \geq \gamma_{i-1,j}, \quad \forall (v_{i-1}, v_i) \in E.$$

Since less transmission quality $\left. \frac{E_b}{I_0} \right|_{i-1,j}$ will need less the power cost $c(v_{i-1}, v_i)$ from node v_{i-1} to node v_i in graph G (Section 2.6.2). As the transmission quality $\frac{E_b}{I_0}$ of a link is decreasing, the power costs of the link will be decreasing. Therefore, the optimal solution to have minimum power cost $C(\zeta)$ is that all SIR constraints should be met with equality, i.e., $\left. \frac{E_b}{I_0} \right|_{i-1,j} = \gamma_{i-1,j}$, $\forall (v_{i-1}, v_i) \in E$. After taking $\left. \frac{E_b}{I_0} \right|_{i-1,j} = \gamma_{i-1,j}$ to allocate the

transmitted power of each link in QCMP CAHAN, a minimum-power-allocated graph $G_{\min P}$ is formed. In the graph $G_{\min P}$, the minimum required SIR is achieved at each receiver. The SIR constrained shortest path can be found by running the Dijkstra algorithm on the graph $G_{\min P}$.

2.4 Control Message Energy/Bandwidth Consumption Analysis

2.4.1 Terminology and Definition

Since the control messages are signaling overhead, the number of control messages needs to be minimized for the sake of system capacity. The terminologies of the message overhead and radio resource (channel bandwidth & transmitted power) consumption are described below.

1. *Control message overhead* η is defined to be the total number of transmitted control packets in an update interval.
2. *Control packet energy consumption* ε is defined to be the total energy consumption (joules) of transmitted control packets in an update interval.

$$\varepsilon = \sum_{i=1}^{\eta} (P_i T_i) \quad \text{where } T_i = \frac{l_i}{R_i} \quad (2.21)$$

η control message overhead in an update interval

P_i transmitted power of control packet i

T_i transmission time of control packet i

l_i length (bits) of control packet i

R_i transmission rate (bps) of control packet i

3. *Control channel bandwidth consumption* β is used for control channel bandwidth measure and is defined to be the total number of transmitted control message bits in an update interval.

$$\beta = \sum_{i=1}^{\eta} l_i \quad (\text{bits/interval}) \quad (2.22)$$

2.4.2 Control Message Overhead / Radio Resource Theoretical Analysis

1) *HELLO Control Message:*

$$\text{HELLO control message overhead } \eta = \aleph \quad (2.23)$$

$$\text{HELLO control packet energy consumption } \varepsilon = \sum_{i=1}^{\eta} (P_i T_i) = \sum_{i=1}^{\eta} (P_{br,i} \frac{l_{Hello}}{R}) \quad (2.24)$$

$$\text{HELLO control channel bandwidth consumption } \beta = \sum_{i=1}^{\eta} l_i = \eta l_{Hello} = \aleph l_{Hello} \quad (2.25)$$

\aleph total number of MTs in networks

P_{br} MT broadcast power

l_{Hello} Hello control packet length (bits)

R transmission rate (bps)

2) *NEUP Control Message:*

$$\text{NEUP control message overhead } \eta = \aleph - \sigma \quad (2.26)$$

$$\text{NEUP control packet energy consumption } \varepsilon = \sum_{i=1}^{\eta} (P_i T_i) = \sum_{i=1}^{\eta} (P_{up,i} \frac{l_{NEUP,i}}{R}) \quad (2.27)$$

$$\text{NEUP control channel bandwidth consumption } \beta = \sum_{i=1}^{\eta} l_i = \sum_{i=1}^{\eta} l_{NEUP,i} \quad (2.28)$$

\aleph total number of MTs in networks

σ number of isolated MTs in networks

$P_{up,i}$ uplink power of NEUP packet from MT i to BS

$l_{NEUP,i}$ NEUP control packet length (bits) of MT i

3) *RUP Control Message:*

$$\text{RUP control message overhead } \eta = \aleph_s - \sigma_s \quad (2.29)$$

$$\text{RUP control packet energy consumption } \varepsilon = \sum_{i=1}^{\eta} (P_i T_i) = \sum_{i=1}^{\eta} (P_{down,i} \frac{l_{RUP,i}}{R}) \quad (2.30)$$

$$\text{RUP control channel bandwidth consumption } \beta = \sum_{i=1}^{\eta} l_i = \sum_{i=1}^{\eta} l_{RUP,i} \quad (2.31)$$

\aleph_s number of “source MTs” in networks

σ_s number of isolated “source MTs” in networks

$P_{down,i}$ downlink power of RUP packet from BS to MT i

$l_{RUP,i}$ RUP control packet length (bits) of MT i

2.5 Mobility Management, Resource Management, and Admission Control

Provisioning of QoS for multimedia traffic in wireless networks is complicated due to user mobility and limited wireless resources. The MT positions may change frequently, and the radio resource is scarce. The development of an integrated framework for QoS provisioning at a low layer will combine various approaches for mobility management, resource reservation and admission control.

2.5.1 Mobility Management

In the mobility management, the MT positions may change frequently such that the power cost of the topology table in BS should be updated periodically. By sending the NEUP packets with updated link power cost periodically, the total probability of error in the topology table of the BS can be improved. In QCMP CAHAN, the functionality on the MT is minimized in order to save MT battery power and user equipment costs. However, the process of information update itself consumes computational and transmission energy. When the update interval is longer, the less energy is consumed by updating process, at the cost of less accurate topology and power information. On the other hand, when the update interval is shorter, more energy is consumed by the updating process, but QoS could be guaranteed. Therefore, the optimization of the update interval is crucial to the minimization of total probability of error in topology and power information. Let C_{error} denote the cost of energy consumption per unit time due to the link power error, C_{update} denote the cost of a single process of update that consumes all the energy, and τ denote the update interval. C_{error} is a nondecreasing function of τ , i.e., $C_{error} = f(\tau)$. The total average cost per unit time for the energy consumption for each MT, C_{total} is

$$C_{total}(\tau) = C_{error} + \frac{C_{update}}{\tau}, \quad \tau > 0 \quad (2.32)$$

For simplicity, we normalize C_{error} by C_{update} . The function $\beta(\tau)$ is defined as the ratio of C_{error}/C_{update} . The previous relation becomes

$$C_{total}(\tau) = C_{update} \left(\frac{C_{error}}{C_{update}} + \frac{1}{\tau} \right)$$

$$= C_{update} \left(\beta + \frac{1}{\tau} \right). \quad (2.33)$$

In the QCOMP CAHAN, the C_{update} is the energy consumption of a single update process, which is the total energy consumption of HELLO and NEUP packets in an update interval. The length of the HELLO packet is constant. BSs know the broadcast power of the HELLO packet, the length of each NEUP packet, and the uplink power of MTs. Therefore, in each update interval, C_{update} can be estimated by BSs. Moreover, $\beta(\tau)$ is a nondecreasing function of τ and depends on the system mobility model ($\beta(\tau)$ can be approximated by theoretical model). C_{total} will change with different value of update interval τ . We know that $(C_{update} \beta(\tau)) \rightarrow 0$ as $\tau \rightarrow 0$. However, $\tau \rightarrow 0$ implies an infinite number of update messages, i.e., $(C_{update}/\tau) \rightarrow \infty$. Clearly, the minimization of C_{total} yields the optimal value of τ .

Assume that $C_{total}(\tau)$ is continuously differentiable function. The optimal solution of the problem in (2.33) must satisfy the first-order optimality conditions

$$\nabla_{\tau} C_{total}(\tau) = 0. \quad \text{i.e.,} \quad (2.34)$$

$$\frac{\partial C_{total}}{\partial \tau} = C_{update} \left(\frac{\partial \beta(\tau)}{\partial \tau} - \frac{1}{\tau^2} \right) = 0. \quad (2.35)$$

Therefore, the optimality conditions for the problem (2.33) is

$$\frac{\partial \beta(\tau)}{\partial \tau} = \frac{1}{\tau^2} \quad \tau > 0 \quad (2.36)$$

Other alternative approach to find the optimal solution of problem (2.33) is the gradient decent methods (steepest decent method or Newton's method). The Iteration of the searching of the gradient decent method will be processed until $\nabla_{\tau} C_{total}(\tau) = 0$.

The position of each MT changes over time. In QCMP CAHAN, the update interval can be adaptively adjusted in different period for cost effectiveness. With the mobility management, the QCMP CAHAN protocols can dynamically update its links in order to maintain connectivity, and hence the QCMP CAHAN protocols are a self-reconfiguring. It can be seen that the protocols are also fault tolerant. A network protocol is fault tolerant if it is self-reconfiguring when MTs leave or new MTs join the network [32].

2.5.2 Resource Model/Management

In order to support a wide variety of applications (such as voice, audio, video, image, data, and web browsing) with varying QoS specifications, the wireless resources that these applications require in QCMP CAHAN have to be allocated appropriately. The role of the resource management is to map the QoS requirements of the various applications to network resources. The resource allocation and QoS go hand in hand in a wireless system. The QoS requirements can be expressed in terms of several important parameters: packet delay, minimum bandwidth (throughput) requirement, and maximum packet loss/error rate [33]. The end-to-end delay in QCMP CAHAN is related to the radio-link count between BS and MTs. To establish radio links between two wireless devices, the system has to assign 1) an access port 2) a channel 3) a transmitter power for radio link. The maximum packet error rate (PER) is related to the signal-to-interface ratio (SIR) requirement in a power allocation scheme. Therefore, we address the issue of resource management in QCMP CAHAN in terms of power allocation as well as transmission bandwidth allocation. Resource management can be performed on a global or incremental basis [33]. The global resource management entails renegotiation of

resource each time while a session is activated or leaves the system. A session is defined as the transmission of a message sequence from the transmitter to the receiver. However, the incremental scheme is statically allocated only once per session, and incoming session resource allocation has to fit around the other fixed session allocations. The global resource management has ability to reevaluate resource allocation decision as needed and utilize resource very efficiently. However, the global resource management is highly computationally intensive and entails a lot of overhead in a distributed system, since it requires that the entire state of the system be known at each decision interval [33]. Therefore, the global resource management is well suited to the centralized cellular system in QCMP CAHAN, where the BS can monitor all activity and make reallocation decisions as required. On the other hand, the incremental scheme is better suited to distributed ad hoc system in QCMP CAHAN. An incremental resource allocation scheme for multirate CDMA ad hoc system, which is named the distributed resource negotiation protocol, is proposed in [33].

In CDMA networks, the transmission power and data rates are the core resources to be managed and allocated. There could be three different optimal criteria for resource allocation in wireless networks, i.e., minimum power allocation, maximum rate allocation, and maximum SIR allocation [33][45]. The minimum power allocation scheme is one of the most widely utilized resource allocation schemes. The object of minimum power allocation metric is to minimize the total transmitted power such that the maximum number of users of each class can be simultaneously supported in the CDMA cellular system due to the minimum interference. In the minimum power allocation scheme, the minimum required data rate is allocated to each session and the minimum

required SIR is achieved at the receiver. This scheme emphasizes conservation of transmission power, and only the minimum transmission power required to achieve the minimum requirement of data rate and SIR is allocated. Differently, in the maximum rate allocation, only the minimum required SIR is allocated, and it attempts to achieve the best possible throughput for current users in a cell by adding extra transmitted power, over that required to support the minimum data rate and SIR. But, the adding extra transmitted power to increase the data rate of each MT will introduce more interference into a cell. In the maximum SIR allocation scheme, only minimum required data rate is allocated, and any extra power ration is used to increase the SIR of a session, i.e., the SIR at receiver is maximized by allocating a maximum transmission power. The maximum SIR allocation scheme will also introduce more interference into a cell. The network capacity (number of users) of CDMA system is interference limited. Therefore, the minimum power allocation scheme in CDMA cellular system (with global resource management) will have minimum power consumption and the highest network capacity, as compared with other two schemes above [45][33]. However, while using the minimum power allocation scheme (with minimum required SIR in each session), the incremental resource management in ad hoc networks may increase the blocking rate of the incoming session. As mentioned above, in the incremental scheme, resource are allocated only once per session and the incoming session has to fit around the session already there. In the incremental resource management, a session that has been allocated the minimum required SIR cannot sustain any additional interference from incoming session without losing its QoS guarantees. This leads to a single session blocking all other incoming sessions. On the other hand, the maximum SIR allocation scheme has maximum SIR in

each session such that it allows other spatially dispersed MTs to setup sessions successfully. Therefore, in the CDMA ad hoc systems with the incremental resource management, the maximum SIR allocation scheme may have highest throughput, and the minimum power allocation scheme will have minimum power consumption [33]. However, the throughput performance of the minimum power allocation scheme in the ad hoc system can be improved by 1) Decreasing the time duration of each ongoing session. This will decrease the blocking rate of an incoming session and the blocking duration. 2) Increasing the value of the maximum sustainable interference (MSI) advertised by an ongoing session. This will allow more sessions to be created while still satisfying the new MSI constraint [33].

In the resource allocation policy, we use the minimum power allocation scheme for the cellular system of QCMP CAHAN. The ad hoc system of QCMP CAHAN can use either the maximum SIR allocation scheme with the throughput consideration or the minimum power allocation scheme with the power consideration. The minimum-power allocation schemes for multirate CDMA cellular/ad hoc system are proposed in [33] [46].

Let $\{i, j\}$ denote the session from transmitter MT i to receiver MT j . The minimum transmission power allocation in cellular/ad hoc system is given:

1) Ad hoc systems

$$\bar{P}_{i,j}^{\min} = \frac{\gamma_{i,j}^{ah} r_{i,j}^{ah} \xi_{i,j}}{\alpha_{i,j} \omega_{ah}}. \quad (2.37)$$

$$\xi_{i,j} = \sum_{\{m,l\} \neq \{i,j\}} \bar{P}_{m,l} \alpha_{m,j} + \eta_0 \omega_{ah} \quad (2.38)$$

where $\bar{P}_{i,j}^{\min}$ denotes the minimum transmitted power from MT i to MT j , $\gamma_{i,j}^{ah}$ denotes the

minimum SIR requirement for $\{i, j\}$, $r_{i,j}^{ah}$ denotes the minimum requirement of data rate for $\{i, j\}$, $\xi_{i,j}$ denotes the total interference experienced by $\{i, j\}$, $\alpha_{i,j}$ denotes the attenuation from MT i to MT j , ω_{ah} denotes available bandwidth in ad hoc communication system, $\bar{p}_{i,j}$ denotes the transmitted power from MT i to MT j , and η_0 denotes the thermal noise spectral density.

2) Cellular system

a) Uplink from MT i to BS v

$$P_{i,BS}^{\min} = \frac{\gamma_{i,BS}^c r_{i,BS}^c \left(\sum_{j \in S, j \neq i} P_{j,BS} \alpha_{j,BS} + I_{extMT,BS} + \eta_0 \omega_c \right)}{\alpha_{i,BS} \omega_c} \quad (2.39)$$

b) Downlink from BS v to MT i

$$P_{BS,i}^{\min} = \frac{\gamma_{BS,i}^c r_{BS,i}^c \left(\alpha_{BS,i} \sum_{j \in S, j \neq i} P_{BS,j} + I_{extBS,i} + \eta_0 \omega_c \right)}{\alpha_{BS,i} \omega_c} \quad (2.40)$$

where $P_{i,BS}^{\min}$ denotes the minimum transmitted power from MT i to BS v , $P_{BS,i}^{\min}$ denotes the minimum transmitted power from BS v to MT i , $\gamma_{i,BS}^c$ denotes the minimum SIR requirement from MT i to BS v , $r_{i,BS}^c$ denotes the minimum requirement of data rate from MT i to BS v , s denotes the set of MTs being served from the BS v , $P_{i,BS}$ denotes the transmitted power from MT i to BS v , $\alpha_{i,BS}$ denotes the attenuation from MT i to BS v , $I_{extMT,BS}$ denotes the total external interference from MTs being serviced by other than BS v (as experienced by the receiver of BS v), $I_{extBS,i}$ denotes the total external interference from BSs other than BS v (as experienced by the MT i), ω_c denotes available bandwidth in cellular system, and η_0 denotes the thermal noise spectral density.

As mentioned before, the CDMA spreading code in the cellular system and the ad hoc communication system is assigned individually. The purpose of the code assignments is to spatially reuse spreading codes to reduce the possibility of packet collisions and to react dynamically to topological changes. In each individual communication system, we assume that there are always a sufficient number of spreading codes that can be assigned to MTs such that it will assign distinct spreading codes to different MTs without code assignment problem. However, when the number of the orthogonal spreading codes is limited and is smaller than the number of MTs in the network, the spatial reuse of the spreading codes is needed. The number of the orthogonal spreading codes is a design parameter for the CDMA orthogonal code sets. A distributed spreading code assignment protocols with few codes can be found in [35]. In general, spreading code assignment protocols attempts to assign spreading codes to MTs with the constraint that all neighbors of a MT have distinct spreading codes [47]. Moreover, an alternative spreading code strategy to the fixed spreading code assignment of CDMA systems is code-hopping [48]. In code-hopping scheme, mobile users swap their spreading codes according to a predetermined hopping pattern. By changing the spreading code sequences of the MTs in consecutive signal intervals, probability of having a mobile which suffers from high interference in a long burst of signal intervals is decreased such that the trapped MTs have less interference in the pursuing intervals. The code hopping scheme constitutes a simple alternative strategy to the complicated task of dynamic channel (code) allocation.

The spreading gain of a terminal is the ratio of the signal bandwidth after spreading (i.e., the channel bandwidth) to the bandwidth before spreading, or equivalently, the ratio of the time duration of a transmitted bit to the time duration of a

chip. The spreading of a terminal is controlled by dynamically increasing/decreasing the time duration of a transmitted bit, i.e., the transmission rate, while maintaining a constant chip rate (the channel bandwidth). The different data rate can be adjusted by the variable spreading gain (VSG) implementation. CDMA utilizing orthogonal variable spreading factor, by means of which a wide range of data rate values are easily obtained [49]. Consider a terminal i that generates an information bit stream of rate R_i . The information bits are spread by a pseudo noise (PN) code sequence with N_i chips per information symbol to obtain a transmission bandwidth of ϖ . The processing gain (spreading gain) Q_i for terminal i is given by [33][49]

$$Q_i = \frac{\varpi}{R_i} \quad (2.41)$$

The multirate CDMA scheme supports multiple data rates by varying the processing gain. Obviously, terminals transmitting at lower bit rates will have higher processing gains.

2.5.3 Admission Control

Admission control guarantees the feasibility of the QoS specifications for all users and restricts the number of users in the system such that QoS requirements can be met. The objective of admission control is to maximize the utilization of resource under the QoS requirements for all users are guaranteed. An integrated for QoS provisioning is to provide different treatment at a low layer to the two important classes of wireless multimedia traffic –those generated respectively by real-time (delay-sensitive) and non-real-time (delay-tolerant) applications. Dynamic Admission control scheme should adapts to changes in traffic pattern and is stable under overloading traffic conditions such that it can deal with burst data and sudden traffic surges. Admission control scheme guarantees

the priority of handoff call requests over new call requests. For the cellular system, the existing approaches of admission control policy may be broadly characterized as follows [42]: 1) Complete sharing policy: A policy that accept a new user if and only if the BS has sufficient capacity to simultaneously accommodate the SIR requirement of all presently active users and the new user. 2) SMDP approach: the theory of semi-markov decision processes (SMDPs) is used to construct optimal admission control policies 3) Threshold policy: a new class k user is accepted if the number of active class k users is less than a threshold T . The thresholds are then optimized empirically to achieve desired maximum blocking probabilities for the various classes. Moreover, for the ad hoc system, the admission control policy in peer-to-peer communication is proposed in [33][43].

The effect of admitting a new user depends heavily on the QoS requirements (SIR or data rate) of the new user. In the cellular system, a user with a high SIR requirement will reduce network capacity (number of users) more than a user with low SIR requirements due to the interference limitation. In ad hoc system, a route is taken by a stream of packets. When a new user is added to the ad hoc system, the ability of the system to support additional data traffic is reduced [44]. Although transmission on multihops reduces the interference, at the same time the network traffic is artificially increased due to several transmissions of the same packet by intermediate hops. For a multihop network, the capacity is referred to the total traffic rate.

The QCMP CAHAN involves the 4G concept that it is a ubiquitous wireless communication systems and seamless high-quality wireless services. The admission control mechanism in QCMP CAHAN determines an MT's incoming message will be admitted to BS via cellular system or ad hoc system, and how to allocate the limited

resource to users in an efficient way in order to guarantee the users' QoS requirements. The QCMP CAHAN hybrid overlaid admission mechanism can be: 1) An MT first tries to access to BS via the cellular system. The priority of real-time application requests (ex. voice) is over non-real-time application requests (ex. Internet browsing). BS measures and renegotiates the wireless resource for each incoming request. If the BS is able to simultaneously accommodate the minimum QoS requirements of all presently active users and that of new user (i.e., the feasible solution of resource allocation problem exists), admit new connection request. Otherwise, it will redirect the new connection request via ad hoc system or wait a certain time then repeat this request. 2) If no packet is sent via ad hoc system, the ad hoc system will be idle and sleeping. Once the packet is delay-tolerant (non-real-time applications), the packet will be delivered to BS via ad hoc relay. The ad hoc communication range will be adjusted flexibly until it reaches its maximum tolerant hop count and minimum QoS requirement, which are related to end-to-end delay and throughput. MT should constantly monitor the channel quality. If they feel the channel quality is low, they may request for reconfiguration of their connection to BS. 3) The multihop packet relaying may be also triggered for increasing network capacity in hot spot cell, increasing reach ability for those MT in dead spots (i.e., the place where the signals from BS cannot reach), connecting between two MT in close proximity, or extending the physical path of connection without BS. If the packet can be relayed from the high-traffic cell to the low-traffic cell, the traffic will be balanced. The decision of multihop connection can be triggered by both BS and individual MT depending on their needs.

2.6 Channel Model and Power Consumption Model

2.6.1 Channel Model

The most common channel model used for RF systems has path loss, lognormal shadowing, and Rayleigh fading components [9]. Both theoretical and measurement-based propagation models indicate that average received signal power decreases logarithmically with distance. The average large-scale path loss is expressed as a function of distance with a path loss exponent n , where n depends on the specific propagation environment. Also, the surrounding environmental clutter may be vastly different at any two locations having the same separation distance. The large-scale shadowing is modeled by the log-normal distribution. When the multipath exists, two or more versions of the transmitted signal cause the small-scale fading. The Rayleigh distribution is commonly used to describe the statistical time varying nature of the received envelope of a flat fading signal. A simple channel model can be found in [50]. The channel attenuation in this channel model is expressed as a function of distance with a path loss exponent, lognormal random variable representing shadowing, and complex zero-mean Gaussian random variable representing Rayleigh fading.

During the coarse sessions, the channel might be subject to fading or shadowing due to mobility or obstacles in the propagation path. Fast closed loop power control of CDMA system, takes care of these fluctuations in an effort to maintain the desired QoS. The bi-directional closed loop power control can be found in both CDMA2000 system and W-CDMA system [53-54].

2.6.2 Power Consumption Model & Transmission Quality

We assume that our system consists of an arbitrary number of services by considering that each MT is associated with a different quality of service (QoS) requirement. The maximum packet error rate (PER) in the QoS requirement can be mapped into an equivalent signal-to-interference ratio (SIR) requirement. Let E_b denote bit energy and I_0 denote total interference density. The transmission quality E_b/I_0 should be greater or equal to the QoS requirement, i.e., the minimum SIR requirement in MT.

1) *Ad hoc power consumption model of QCMP CAHAN*: As mentioned before, in peer-to-peer model of QCMP CAHAN, we use a multirate CDMA protocol with request-to-send/clear-to-send bandwidth reservation mechanism as the medium access technique. The measure of transmission quality E_b/I_0 from MT i to MT j in the ad hoc communication system of QCMP CAHAN is defined as:

$$\left[\frac{E_b}{I_0} \right]_{i,j}^{ah} = \frac{(\bar{P}_{i,j} \alpha_{i,j}) \omega_{ah} / R_{i,j}^{ah}}{\left(\sum_{\{m,l\} \neq \{i,j\}} \bar{P}_{m,l} \alpha_{m,j} + \eta_0 \omega_{ah} \right)} \quad (2.42)$$

$$\gamma_{i,j}^{ah} \leq \left[\frac{E_b}{I_0} \right]_{i,j}^{ah} \quad (2.43)$$

where $\gamma_{i,j}^{ah}$ denotes the minimum SIR requirement for $\{i, j\}$, $\bar{p}_{i,j}$ denotes the transmitted power from MT i to MT j , $\alpha_{i,j}$ denotes the attenuation from MT i to MT j , ω_{ah} denotes available bandwidth in ad hoc communication system, $R_{i,j}^{ah}$ denotes data rate from MT i to MT j , $\{i, j\}$ denotes the session from transmitter MT i to receiver MT j , and η_0 denotes the thermal noise spectral density.

2) *Cellular power consumption model of QCMP CAHAN*: For the cellular network model

of QCMP CAHAN, two distinct frequency bands between BS and MTs are used separately to carry the information on the upstream and the downstream. The multirate CDMA is the medium access technique between the BS and the MTs. The measure of transmission quality E_b/I_0 in the multirate CDMA cellular network model of QCMP CAHAN can be found in [46].

2.7 Performance Evaluation & Numerical Study

2.7.1 Simulation Model

The simulation model of QCMP CAHAN was implemented using OPNET (Figure 2.2). In the simulation, the initial coordinates of all MTs are generated from an i.i.d. uniform distribution over 7 cells. The Dijkstra/Bellman-Ford algorithm in BS determines the minimum-power routes. All the functions in QCMP CAHAN system model were implemented inside MTs, BSs, and MSC. All of BSs were connected with the same MSC. The simulation has capability to simulate a network with hundreds of MTs.

- 1) *Mobility model*: In each small update interval, the MTs' velocities are constant, and the magnitude component of the velocity is uniformly randomly selected from interval $[0, V_{max}]$, where V_{max} is the maximum moving speed of an MT and is related to the MT mobility. The direction component of the velocity is uniformly distributed in the interval $[0, 360]$ degrees, where "360" is the maximum degree of a circle. The mobility of MTs is restricted within 7 cells.
- 2) *Traffic model*: Two different traffic models are individually used in our uplink traffic simulations and downlink traffic simulations. In uplink traffic simulations, every MT is a source that is sending messages, and all the traffic flows in the

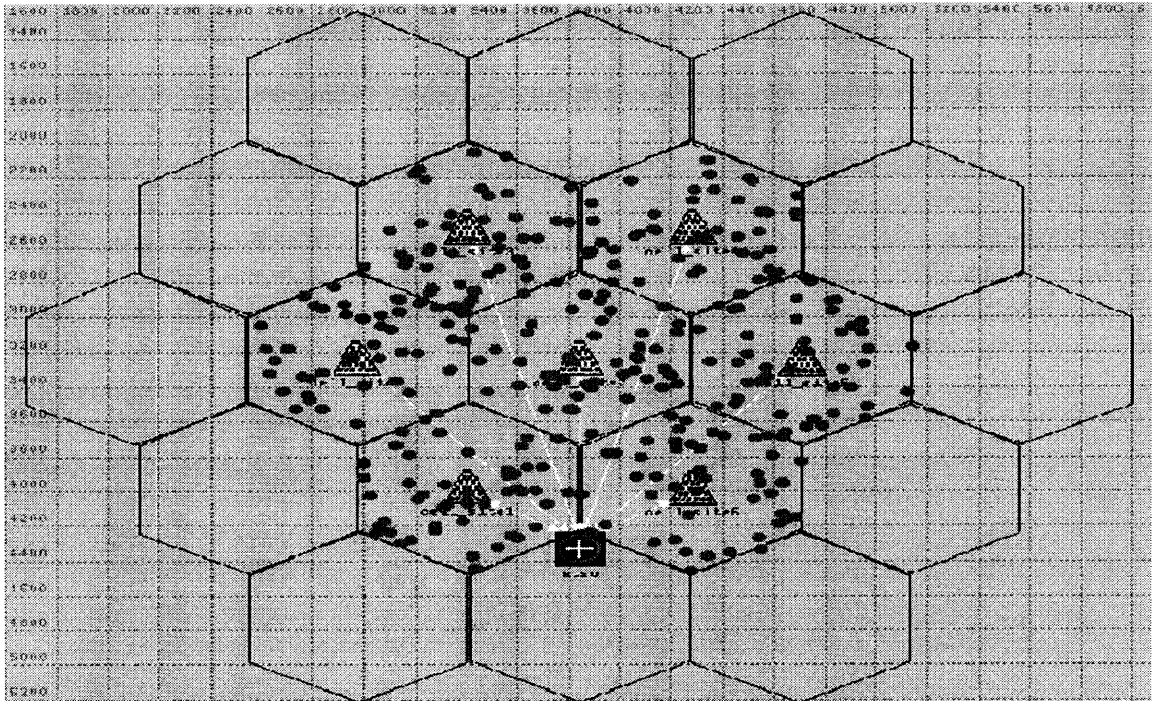


Figure 2.2 OPNET simulation model.

network have destinations outside the MSC range and traverse through the MSC. In downlink traffic simulations, every MT is a destination MT that is receiving messages from the MSC. That is to say, the traffic flows in downlink traffic simulations and the traffic flows in uplink traffic simulations traverse in the opposite direction. In each traffic model, there is only the point-to-point traffic, i.e., a packet has only one destination. Moreover, in each uplink/downlink simulation update interval, each source/destination MT sends/receives exactly two 1250-byte data packets (Each packet has the same length).

Simulation Data Packet Format

QCMP CAHAN needs to encapsulate (precede) each original data packet (1250 bytes) with an additional route information (a sequence of relay MTs).

Original data packet pattern (1250 bytes)

type of services 1 byte	total length (bytes) 2 bytes	message type 1 byte	source ID 2 bytes	destination ID 2 bytes	data 1242 bytes
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The attached route information (≥ 1 bytes) in each original data packet

# of relay MTs 1 bytes	relay MT ID [I] 2 bytes	relay MT ID [II]
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- 3) *Channel model*: The channel attenuation is expressed as a function of distance with a path loss exponent, lognormal random variable representing shadowing, and complex zero-mean Gaussian random variable representing Rayleigh fading. We assume the fading is slow and the fast closed loop power control is available to combat the fading [52] and perfectly tracks the fading channel with no delay. The fast closed loop power control can be implemented in the forward and the reverse directions. The bi-directional closed loop power control can be found in both CDMA2000 system and W-CDMA system [53-54].
- 4) *Power consumption model*: The minimum power allocation scheme is implemented in both cellular system and ad hoc system. We assume all MTs have the same transceiver hardware. The whole power consumption of MT transceiver hardware includes transmitted power, transceiver power, and processing power. The transmitted power refers to the power radiated by the antenna, and the transceiver power refers to the power consumed by the transceiver circuits. However, in the design of modern processors, the processing power consumption required for processing and computation can be made negligible as compared with the transmitted power and the transceiver power in recent low-power processor design [32]. The transceiver power consumption can be modeled as a basic fixed transceiver power consumption (80 mW) consumed at each MT and an additional receiver power consumption (20 mW) to devote part of the transceiver to receive and store messages [32]. This additional receiver power

consumption is only added in the power consumption of the MTs that receive the transmission.

In the simulations, the transceiver power consumption, which refers to the power consumed by the transceiver circuits, affects MT battery energy. However, the transceiver power consumption will not be considered during the comparison of transmitted power consumption between QCMP CAHAN and pure cellular networks since the transceiver power doesn't affect the interference of CDMA systems. In a word, we only consider the transmitted power while comparing the interference of CDMA systems.

The simulations were run for a range of network density. Here, the network density is defined as the average number of MTs being served in a cell site. For each network density, we calculate the total transmitted energy in an update interval. As mentioned above, in each simulation update interval, each destination/source MT will receive/sent just two same-size 1250-byte data packets. In j update interval, the total transmitted energy consumption E_j^T after each destination MT receiving just two same-size data packets is defined as below.

$$E_j^T = \sum_{i=1}^K E_i' . \quad (2.44)$$

where E_i' denotes the transmitted energy consumption of two same-size data packets from BS to a destination MT i along a sequence of relay MTs (or a source MT i to BS along a sequence of relay MTs). K denotes the total number of the destination MTs in downlink transmission (or the source MTs in uplink transmission).

To make smooth simulation results curve on a figure, we repeat the same update

interval for whole network lifetime and take their average. The final simulation results are shown in following subsection. The comparison criterions for QCMP CAHAN and pure cellular networks are: a) Assume that there is no noise. b) Each MT has the same transceiver hardware and QoS requirement. c) There is no packet loss. In our simulations, transmission quality E_b/I_0 is set to meet QoS requirement $\gamma'_{i,v}$. The simulation parameters are shown in Table 2.1.

Table 2.1 QCMP CAHAN Simulation Parameters

Parameters	
Simulation region	7 cells
Diagonal of each hexagonal cell	1000m
Path loss exponent	4
Transmitter antenna gain	1
Receiver antenna gain	1
Maximum communication range (R_{max})	BS : 500m MT: 100m
Transmission Bandwidth (B.W.)	Between BS and MT: 5MHz Between two MTs: 5MHz
Transmission quality E_b/I_0	$\frac{E_b}{I_0} = \gamma'_{i,v}$ ^a

^a $\gamma'_{i,v}$ denotes the QoS requirement from BS v to an MT i , E_b denotes the bit energy, and I_0 denotes total interference density. The transmission quality E_b/I_0 should greater or equal to $\gamma'_{i,v}$. If taking $E_b/I_0 = \gamma'_{i,v}$, it will spend the minimum transmitted power to satisfy the QoS requirement [46].

2.7.2 Simulation Results, Observation, and Discussion

1) *Proximity limitation shortest path for hop-count constraint simulations*: Figure 2.3 shows that the total data packet and control packet energy consumption of cellular networks and QCMP CAHAN with proximity limitation shortest path. The transmitted energy in Figure 2.3 is the average total transmitted energy of the update intervals in network lifetime. The total transmitted energy consumption will include the transmitted energy consumption for the data packets and all the control packets. The maximum

network density that can be supported in pure cellular networks will be 50. That will be described later. The range of the network density in our simulation is from 20 to 34 (per a cell), so the total number of MTs in our 7-cell simulation model is from 140 to 238. The simulation results show that QCMP CAHAN (with two varied ad hoc communication ranges) spends less total transmitted energy than pure cellular networks for each network density. This behavior arises as a result of several reasons.

First, we consider the transmitted energy of QCMP CAHAN and pure cellular networks at a certain network density and a fixed ad hoc communication range. The total transmitted power of cellular networks can be reduced as a result of multihopping in QCMP CAHAN since messages will be forwarded via relay MTs which split the longer transmission distance between two communicating points into two or more short transmission distances. That is one reason why the total transmitted energy of QCMP CAHAN is less than the total transmitted energy of pure cellular networks.

Secondly, for the same value of network density, we compare the total transmitted energy of QCMP CAHAN with the total transmitted energy of pure cellular networks for two different ad hoc communication ranges (75m and 100m). As the ad hoc communication range of each MT is increased, each MT will involve more neighbors and tend to form larger AHSs. As a result more minimum-power relay MTs from BS to a destination MT can be found, and thus the total transmitted power in QCMP CAHAN will be decreased. Using QCMP CAHAN results in significant savings in total transmitted energy as the ad hoc communication range of each MT is increased.

Thirdly, for a fixed ad hoc communication range, the advantage of QCMP CAHAN is more evident when network density is greater. High network density means

more MTs of pure cellular networks are serviced in a cell and its needs more transmitted power. However, when the network density is greater in QCMP CAHAN, more minimum-power relay MTs from BS to a destination MT can also be found. That is the reason why the total transmitted energy of QCMP CAHAN is proportional to network density with a gentler gradient than the total transmitted energy of pure cellular networks. Therefore, a dense cell in QCMP CAHAN will save more transmitted energy in general.

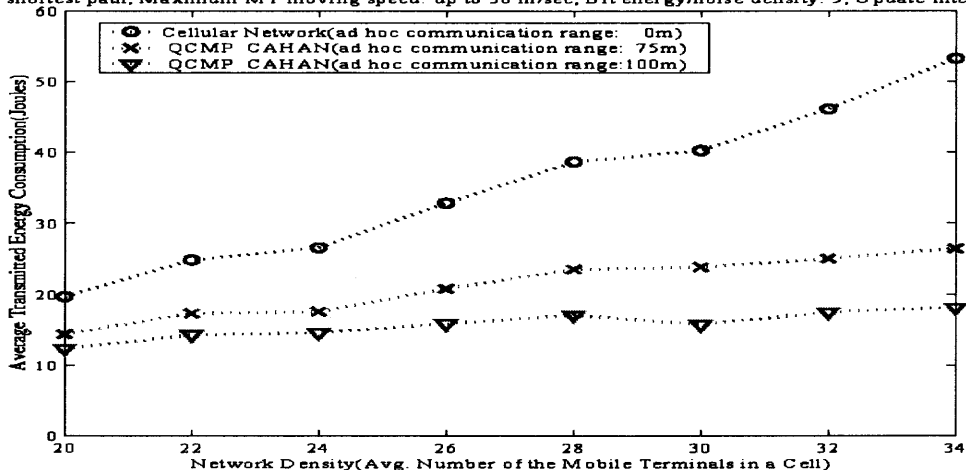
On the other hand, the transmitted power of a transmitter MT in CDMA system is proportional to the transmission distance and the network density [46]. As the network density is increased, the interference increases such that the transmitted power of a MT has to be increased. The network capacity of CDMA system is interference limited. In our simulation environment, the maximum network density that can be supported in pure cellular networks is 50. When the network density is 50, the total transmitted need in the pure cellular networks will approach to infinity. While the pure cellular networks reach its maximum network density that can be supported, QCMP CAHAN can still allow more MTs to enter its cells.

A) Relation between end-to-end hop count and ad hoc communication range:

The maximum number of minimum-power hops $h_{p_{\min}}$ between the BS and the MTs in QCMP CAHAN is a monotonically nondecreasing function of the ad hoc communication range of each MT. Figure 2.4 shows the relation between ad hoc communication range and the maximum number of minimum-power hops between BS and MT within the largest AHS of QCMP CAHAN. The hop count in Figure 2.4 is the average of the hop count over all update intervals in network lifetime and is counted along the minimum-power route. As the ad hoc communication range of each MT is increased, more

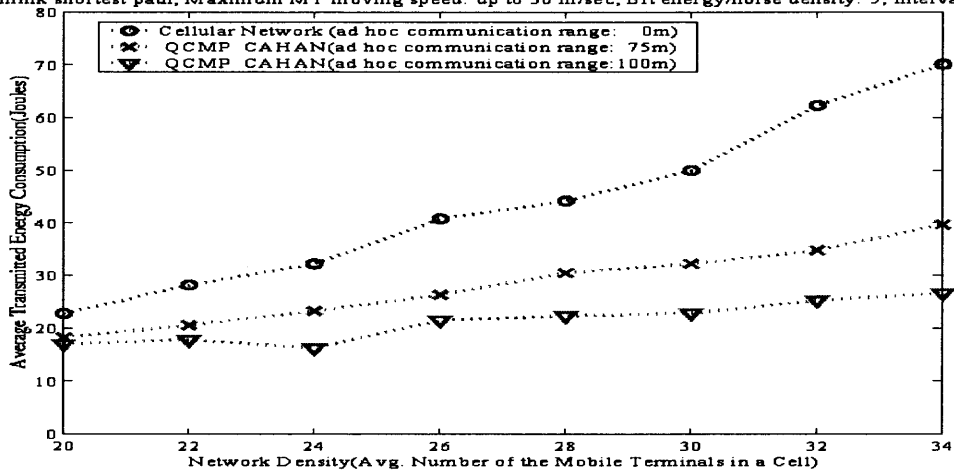
minimum-power relay MTs between BS and MT can be found and hence number of minimum-power hops between BS and MT will be increased. There is a trade-off between transmitted power consumption and end-to-end delay (the hop count between BS and MTs). The ad hoc communication range of each MT in QCMP CAHAN can be increased until the end-to-end delay reaches maximum tolerable value, and the total transmitted power of QCMP CAHAN will reach its minimum possible value. When all the ad hoc communication ranges of MTs in QCMP CAHAN are zero, QCMP CAHAN will become a pure cellular network and the number of the hops between BS and MTs is reduced to one.

Total Data Packet & Control Packet Energy Consumption of Cellular Networks/QCMP CAHAN(Proximity limitation uplink shortest path, Maximum MT moving speed: up to 30 m/sec, Bit energy/noise density: 5, Update Interval: 1 sec)



(a)

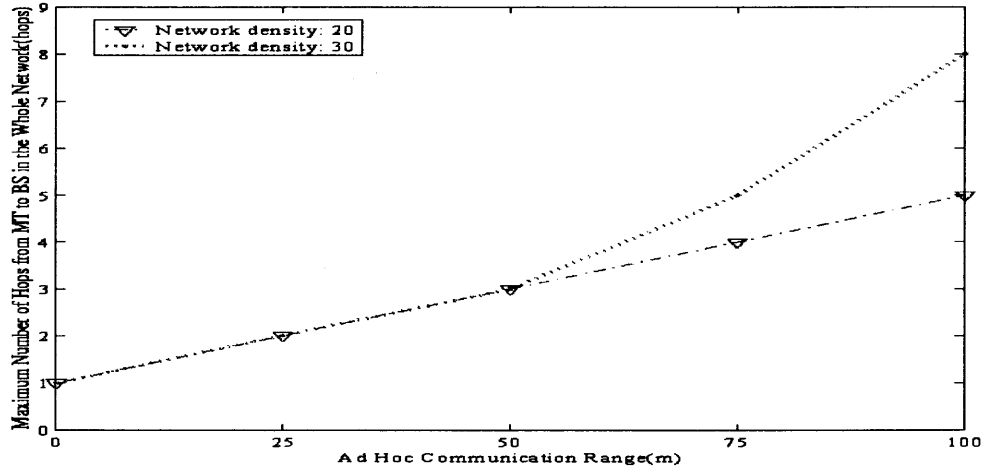
Total Data Packet & Control Packet Energy Consumption of Cellular Networks/QCMP CAHAN(Proximity limitation downlink shortest path, Maximum MT moving speed: up to 30 m/sec, Bit energy/noise density: 5, Interval: 1 sec)



(b)

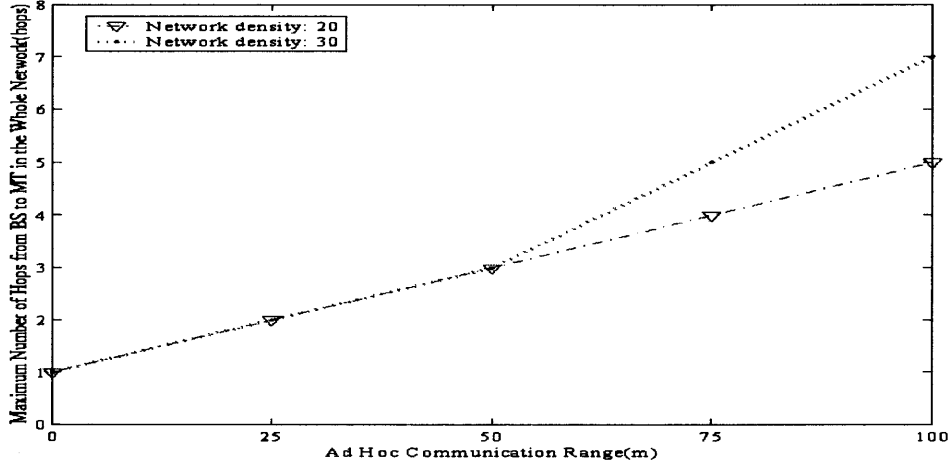
Figure 2.3 Total data packet and control packet energy consumption of cellular networks/QCMP CAHAN with proximity limitation shortest path: (a) uplink traffic simulation, (b) downlink traffic simulation.

Maximum Number of Hops from source MT to BS in the Whole Network of QCMP CAHAN (Proximity limitation uplink shortest path, Maximum MT moving speed: up to 30 m/sec, Update Interval: 1 sec)



(a)

Maximum Number of Hops from BS to destination MT in the Whole Network of QCMP CAHAN (Proximity limitation downlink shortest path, Maximum MT moving speed: up to 30 m/sec, Update Interval: 1 sec)



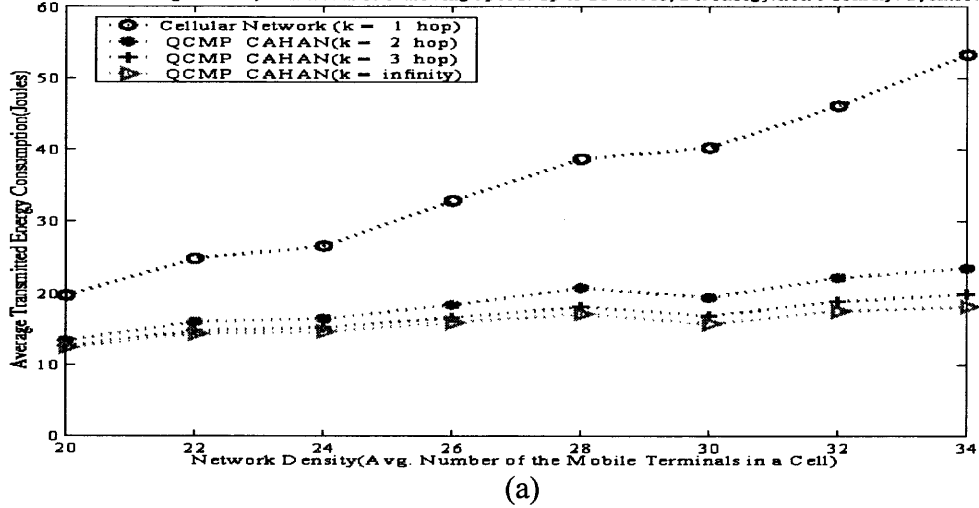
(b)

Figure 2.4 Maximum number of minimum-power hops between MT and BS in the whole network of QCMP CAHAN with proximity limitation shortest path: (a) uplink traffic simulation, (b) downlink traffic simulation.

2) *K-hop limitation shortest path for hop-count constraint simulations:*

At its h th iteration, the Bellman-Ford algorithm identifies the optimal path between a given destination and other nodes, among paths of “at most h hops”. Figure 2.5 shows the total transmitted energy consumption for different k -hop constraints. The k -hop constrained minimum power route is found by using the k -hop constrained Bellman-Ford algorithm. For the same value of network density, we compare the total transmitted energy of QCMP CAHAN with the total transmitted energy of pure cellular networks ($k = 1$) for three different k hop constraints ($k = 2, 3$, and unlimited k). The QCMP CAHAN will be the pure cellular networks as the hop constraint between MTs and BS is 1. When the hop constraint between MTs and BS is increased, the total transmitted energy consumption decreased. Larger number of hop constraint will split the transmission distance between MTs and BS into more number of short transmission distances. Since the channel attenuation is expressed as a function of distance with a path loss exponent, the transmitted power has exponential relation with transmission distance (In our simulation, the path loss exponent is 4)[68][32][9]. Therefore, the total transmitted energy consumption will be decreased the most as k is increased from 1 to 2, as compared with the other situations of the increasing k value.

Total Data/Control Packet Energy Consumption of Cellular Networks/QCMP CAHAN(K- hop limitation uplink shortest path, Ad hoc communication range: 100m, Maximum MT moving speed: up to 30 m/sec, Bit energy/noise density: 5, Interval: 1 sec)



Total Data/Control Packet Energy Consumption of Cellular Networks/QCMP CAHAN(K- hop limitation downlink shortest path, Ad hoc communication range: 100m, Maximum MT moving speed: up to 30 m/sec, Bit energy/noise density: 5, Interval: 1 sec)

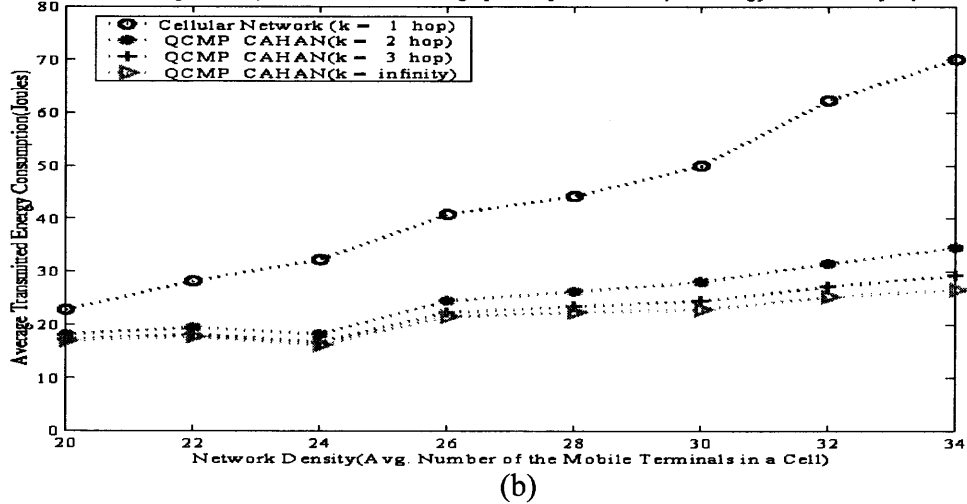


Figure 2.5 Total data packet and control packet energy consumption of cellular networks/QCMP CAHAN with K-hop limitation shortest path: (a) uplink traffic simulation, (b) downlink traffic simulation.

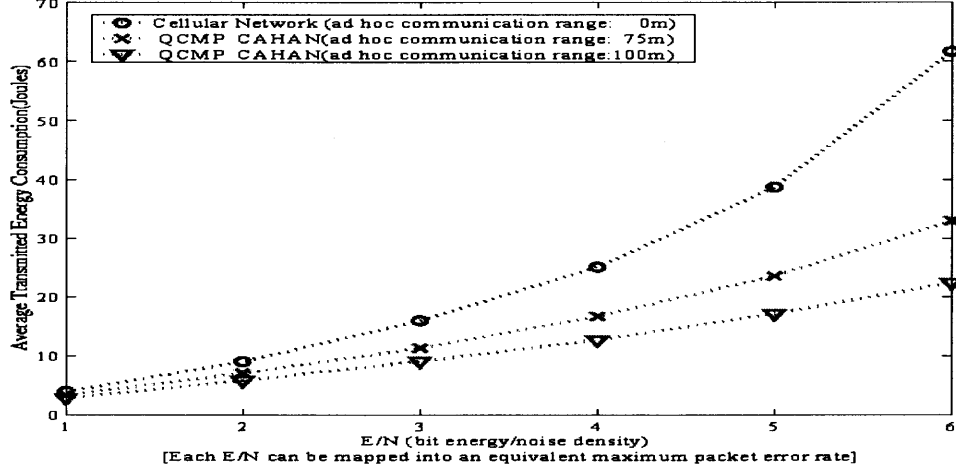
3) *Link-cost limitation shortest path for SIR constraint simulations:*

Let $\frac{E_b}{I_0} \Big|_{i-1,j}$ denote the transmission quality and $\gamma_{i-1,j}$ denote the minimum SIR requirement.

We first taking $\frac{E_b}{I_0} \Big|_{i-1,j} = \gamma_{i-1,j} \quad \forall (v_{i-1}, v_j) \in E$ to allocate the transmitted power of each link

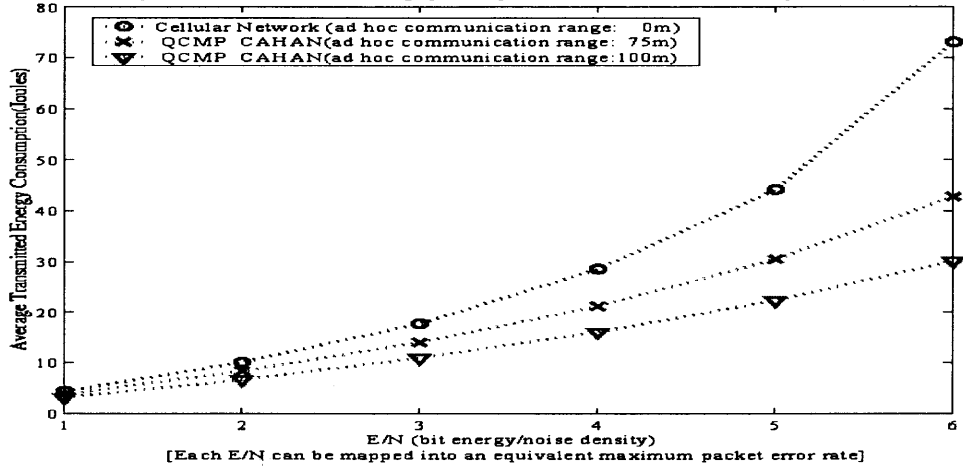
in QCMP CAHAN. After all the power costs are allocated, a minimum-power-allocated graph $G_{\min P}$ will be formed, The SIR constrained shortest path is found by running the Dijkstra algorithm (or Bellman-Ford algorithm) on the graph $G_{\min P}$. Figure 2.6 shows the total transmitted energy consumption for different SIR constrains. In Figure 2.6, the transmission quality $\frac{E}{N}$ is equal to the minimum SIR requirement γ , i.e., $\frac{E}{N} = \gamma$. In the large ad hoc communication range, the advantage of QCMP CAHAN is more evident when SIR constraint is greater. High SIR requirement means more transmitted power cost will be allocated in the radio link. However, when the ad hoc communication range of each MT is large, each MT will involve more neighbors. As a result more minimum-power relay MTs from BS to a destination MT can be found, and thus the total transmitted power in QCMP CAHAN will be decreased. That is the reason why the total transmitted energy of QCMP CAHAN with lager ad hoc communication is proportional to SIR constraint with a gentler.

Total Data Packet & Control Packet Energy Consumption of Cellular Networks/QCMP CAHAN(Link- cost limitation uplink shortest path, Maximum MT moving speed: up to 30 m/sec, Network density: 28, Update Interval: 1 sec)



(a)

Total Data Packet & Control Packet Energy Consumption of Cellular Networks/QCMP CAHAN(Link- cost limitation downlink shortest path, Maximum MT moving speed: up to 30 m/sec, Network density: 28, Update Interval: 1 sec)



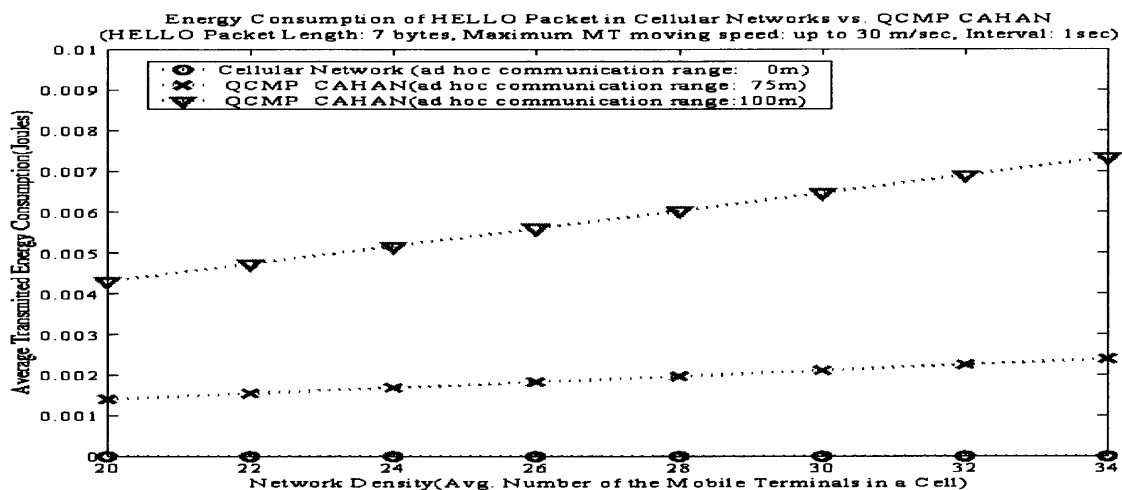
(b)

Figure 2.6 Total data packet and control packet energy consumption of cellular networks/QCMP CAHAN with link-cost limitation shortest path: (a) uplink traffic simulation, (b) downlink traffic simulation ($\frac{E}{N} = \gamma$, γ denote minimum SIR requirement).

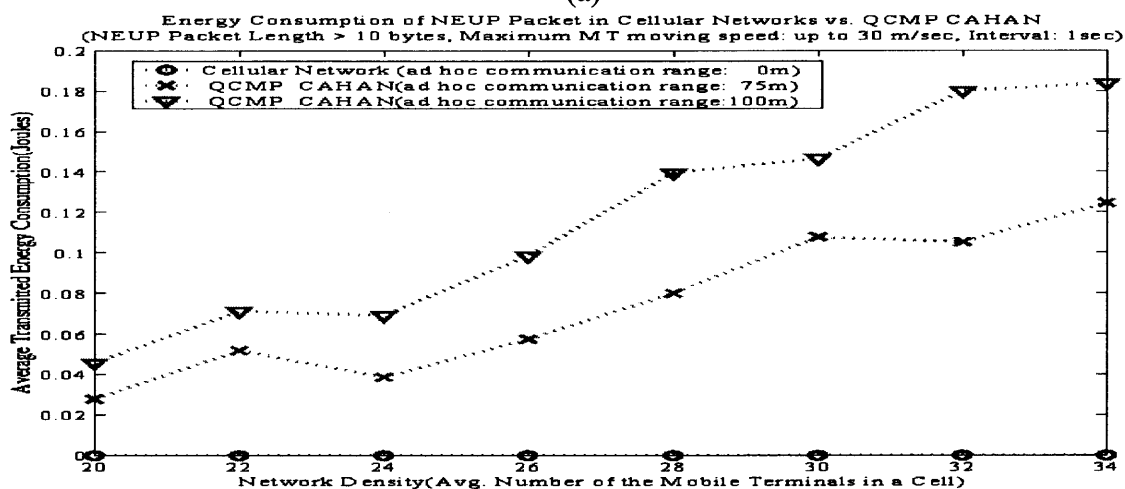
4) *Control message energy consumption and channel bandwidth consumption:*

Since the QCMP CAHAN protocol has to dynamically update its radio links in order to maintain connectivity, some undesired control messages have to be generated. Message overhead (message complexity) refers to the total number of messages transmitted across the network during an update interval. The message overhead also provides insight regarding the scalability of the protocol. QCMP CAHAN needs HELLO, NEUP, and RUP control packets for network system maintenance. During peer-to-peer data transmission, RTS/CTS/ESR/ESA control packets are needed to setup a data session between two MTs. To clearly show the overhead of all the control packets, we evaluate the total control packet energy consumption and the total control channel bandwidth consumption during an update interval (Section 2.4). Figure 2.7 shows the energy consumption of HELLO/NEUP/RUP control packets for system maintenance in QCMP CAHAN, and Figure 2.8 shows energy consumption of RTS/CTS/ESR/ESA control packets for peer-to-peer data transmission in QCMP CAHAN. As the ad hoc communication range (i.e., MT broadcast power P_{br}) of each MT is increased, each MT will involve more neighbors such that NEUP packet length l_{NEUP} , RUP packet length l_{RUP} , and the average number of hops between source MT and BS are increased. From Section 2.4.2, we know that larger ad hoc communication range will have larger energy/channel bandwidth consumption of HELLO, NEUP, RUP, RTS, CTS, ESR, and ESA control packets. The control message energy consumption in Figure 2.7 and Figure 2.8 are small and have been counted into the total transmitted energy in Figure 2.3, Figure 2.5, and Figure 2.6. Moreover, Figure 2.9 shows the HELLO/NEUP/RUP control channel bandwidth consumption for system maintenance in QCMP CAHAN. As

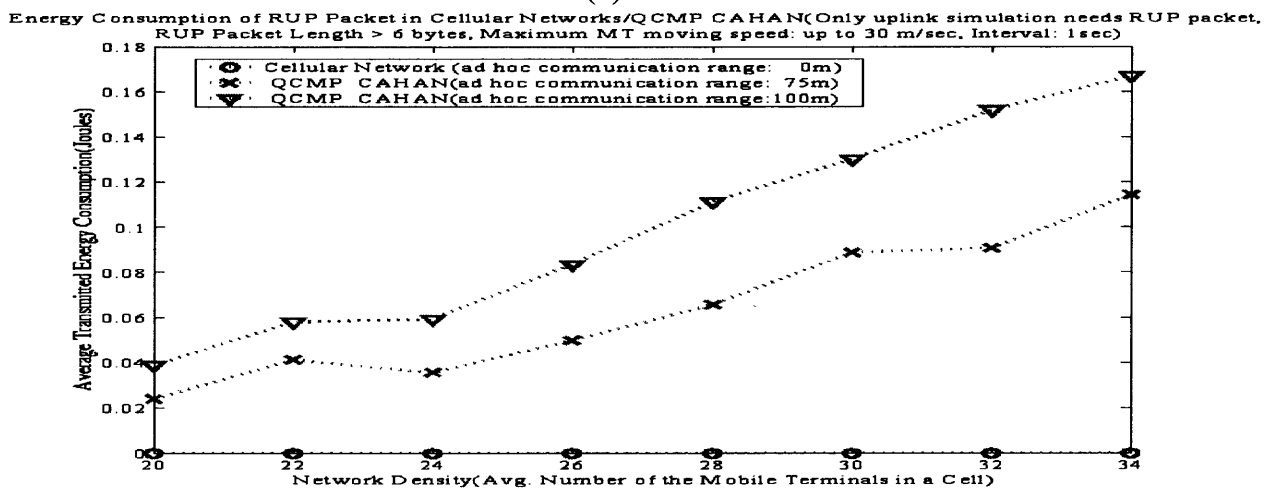
comparing with total number of data message bits received in the destinations during data transmission (Figure 2.10), the control channel bandwidth consumption of the HELLO/NEUP/RUP packet are much less.



(a)



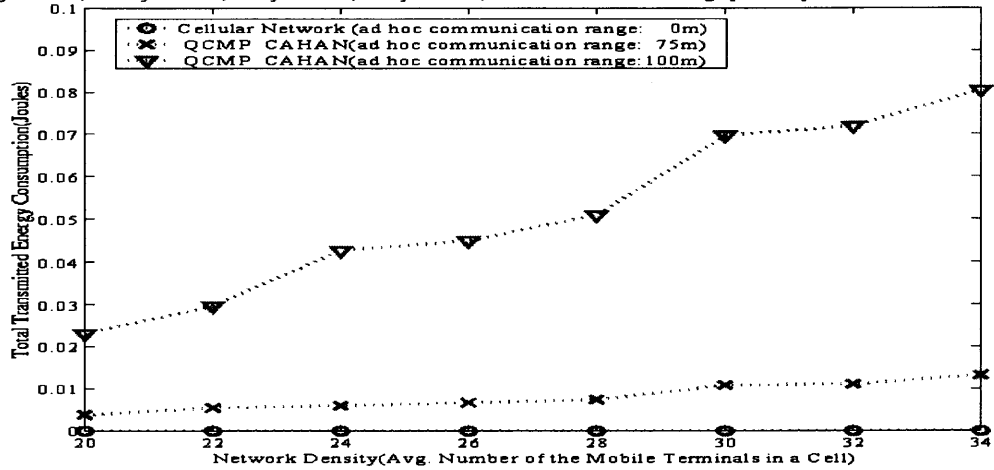
(b)



(c)

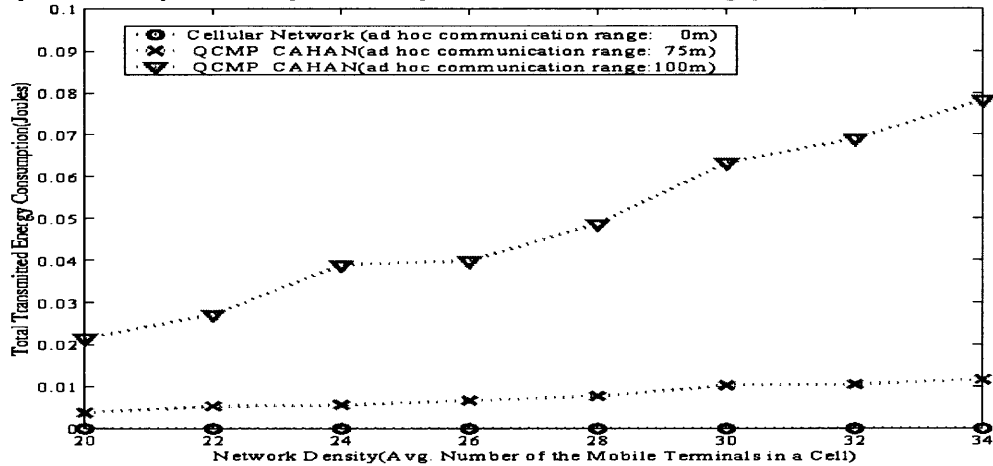
Figure 2.7 Energy consumption of HELLO/NEUP/RUP control packets for system maintenance in QCMP CAHAN: (a) HELLO packets, (b) NEUP packets, (c) RUP packets (RUP packets are needed only if there are source MTs in networks, i.e., RUP packets are needed only in uplink simulation, not downlink simulation).

Energy Consumption of RTS, CTS, ESR, and ESA Packets in Cellular Networks vs. QCMP CAHAN(Uplink, 12- byte RTS, 13- byte CTS, 5- byte ESR, 6- byte ESA, Maximum MT moving speed: up to 30 m/sec, Interval: 1sec)



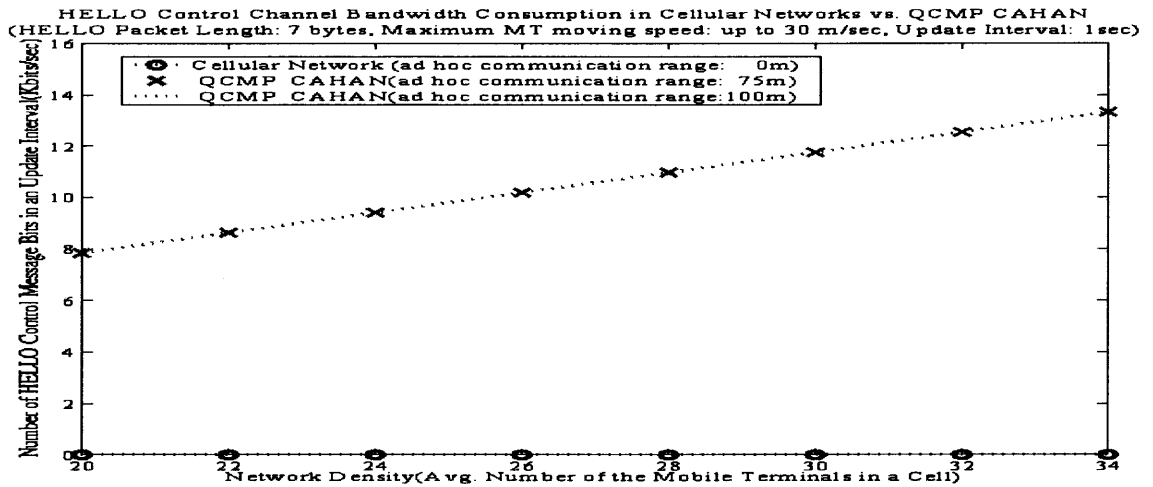
(a)

Energy Consumption of RTS, CTS, ESR, and ESA Packets in Cellular Networks vs. QCMP CAHAN(Downlink, 12- byte RTS, 13- byte CTS, 5- byte ESR, 6- byte ESA, Maximum MT moving speed: up to 30 m/sec, Interval: 1sec)

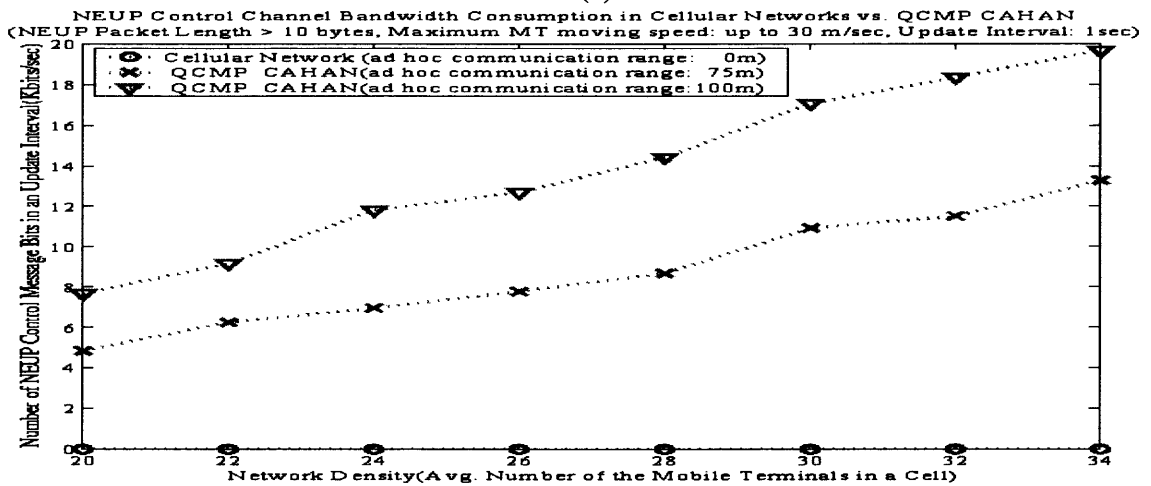


(b)

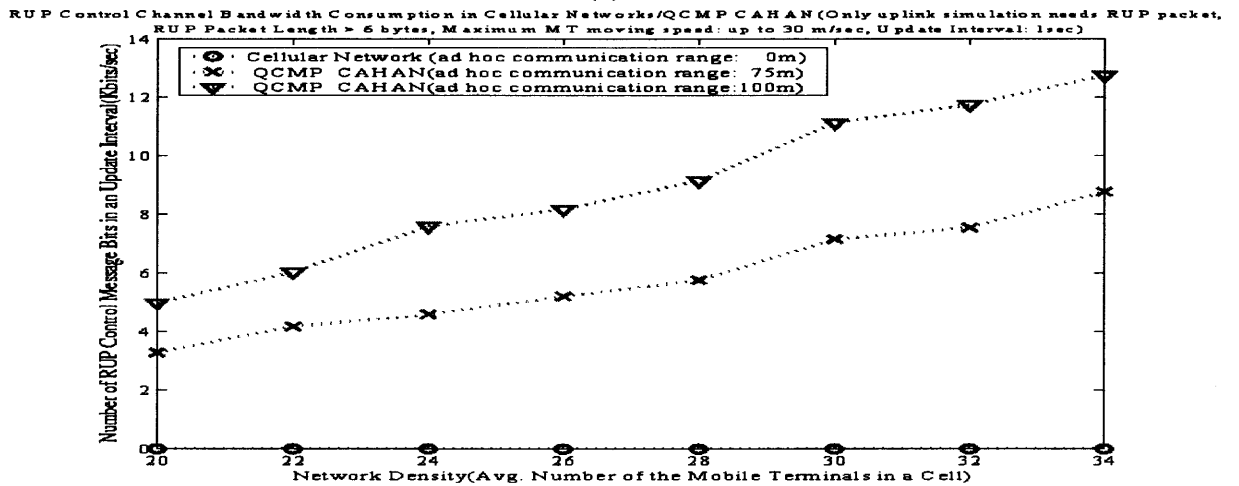
Figure 2.8 Energy consumption of RTS/CTS/ESR/ESA control packets for peer-to-peer data transmission in QCMP CAHAN: (a) uplink traffic simulation, (b) downlink traffic simulation.



(a)



(b)



(c)

Figure 2.9 HELLO/NEUP/RUP control channel bandwidth consumption for system maintenance in QCMP CAHAN: (a) HELLO packets, (b) NEUP packets, (c) RUP packets (RUP packets are needed only if there are source MTs in networks, i.e., RUP packets are needed only in uplink simulation, not downlink simulation).

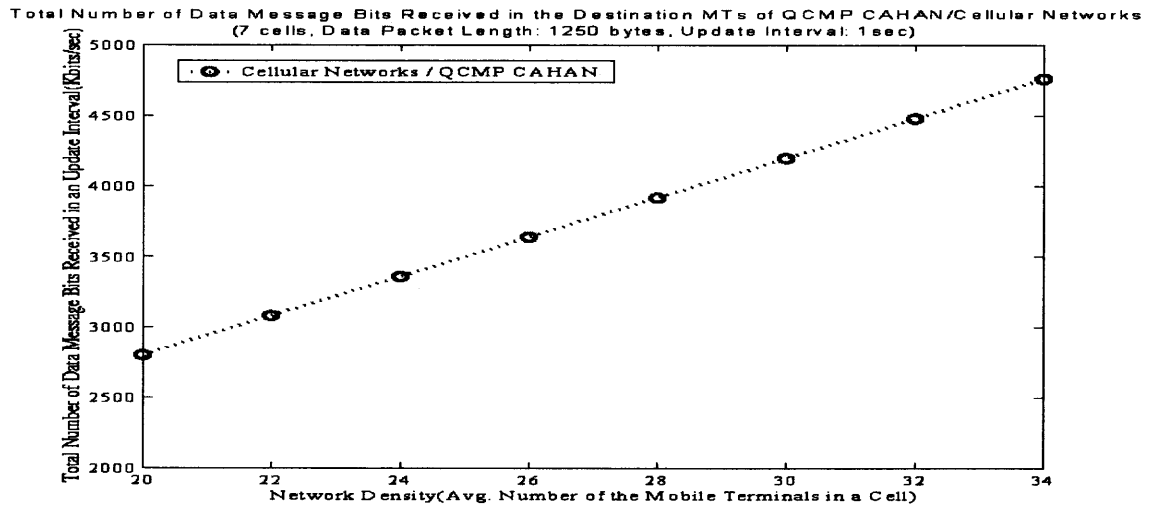


Figure 2.10 Total number of data message bits received in the destinations of QCMP CAHAN/cellular networks in an update interval.

CHAPTER 3

QoS CONSTRAINED NETWORK LIFETIME EXTENSION CELLULAR AD HOC AUGMENTED NETWORK ARCHITECTURE

3.1 Introduction

In multihop cellular networks, the messages need to be forwarded via relay MTs. However, because of various transmission distances or unbalanced traffic load, some relay MTs may tend to drain their batteries faster than others. After a certain number of MTs deplete their battery energy, the network may become disconnected. Depletion of the battery energy of any relay MT will degrade the wireless network performance. Therefore, the network lifetime is defined as the time at which an MT runs out of its battery energy for the first time within the entire network, as defined in [69-71]. In this chapter, we will use the network lifetime of wireless networks as a performance criterion and show how it can be improved.

The major contribution of the work in this chapter is the proposed QoS constraint network lifetime extension cellular ad hoc augmented network (QCLE CAHAN) (Figure 3.1) that bases on the QCMP CAHAN architecture and is designed to achieve the maximum network lifetime under QoS constraints. QCLE CAHAN will have different routing algorithm with QCMP CAHAN. QCLE CAHAN has a hybrid architecture, in which each MT of CDMA cellular networks has ad hoc communication capability. We show that the network lifetime is much higher in the case of QCLE CAHAN than in the case of pure cellular networks and QCMP CAHAN. In downlink transmission of QCLE CAHAN, to save the MT battery energy, the BS will directly send data message to MT via cellular system such that the MTs only need to spend additional energy to receive the

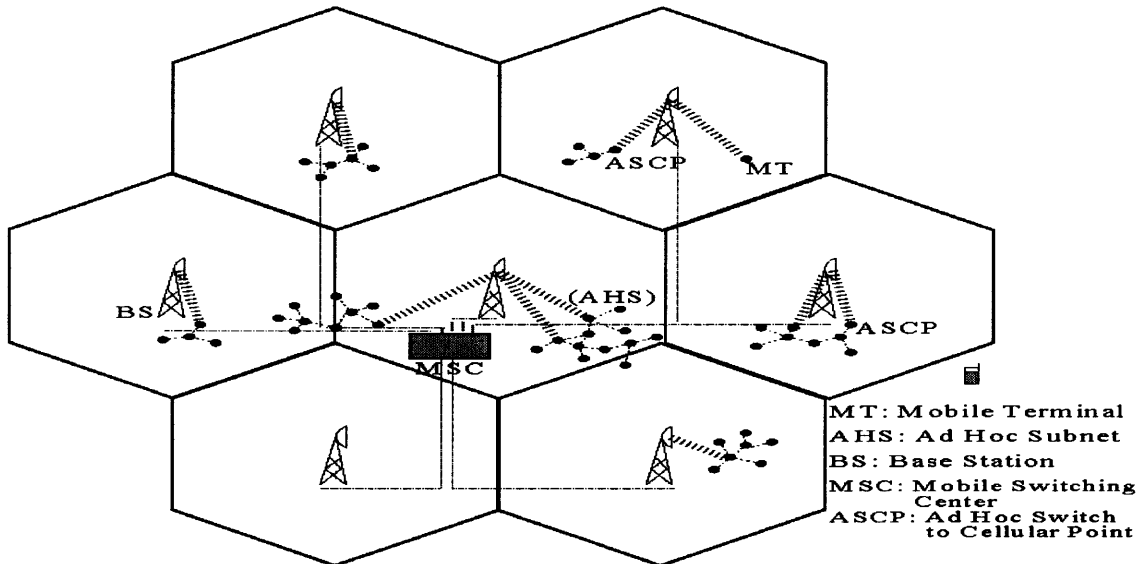


Figure 3.1 QCLE CAHAN architecture.

message. However, in uplink transmission of the QCLE CAHAN, to save the transmission power consumption, only some of the MTs are allowed to send data messages directly to its BS, and these MTs are referred to as the ad-hoc-switch-to-cellular points (ASCP) (Figure 3.1). Only the uplink data messages are relayed to the ASCP and then sent to BS via cellular system. We propose a new energy-balancing scheme that dynamically selects suitable ASCPs according to the MT remaining battery energy such that the selection will balance all the MT battery energy and maximizes its network lifetime. As the number of ASCPs in each ad hoc subnet decreases, the network lifetime of QCLE CAHAN will be extended. On the other hand, as the ad hoc communication range of each MT increases, the network lifetime of QCLE CAHAN increases. Typically, the ad hoc communication range of MTs is shorter than the communication range of the BS. It is assumed that there exists a maximum ad hoc communication range, which is determined by the physical power limitations of an MT. In general, in the QCLE CAHAN architecture, the extension of network lifetime in a denser cell (hot spot cell) will be higher. However, the extension in the network lifetime does not come free. Due to

the increased number of hops involved in information delivery between the source and the destination, the end-to-end delay increases. The number of hops between the BS and the MTs in QCLE CAHAN is a function of the number of the ASCPs and the ad hoc communication range of each MT (that will be explained later). The maximum end-to-end delay will be limited to a specified tolerable value, and QCLE CAHAN has ability to adapt to various delay constraints in different regions, intervals, or services. QCLE CAHAN will reduce to the traditional cellular network if all MTs in a subnet are the ASCPs or their ad hoc communication ranges are zero. All the schemes described in this work can also be applied to any cellular network. We also show that MT mobility is factor potentially influencing the network lifetime of QCLE CAHAN.

3.2 Constrained Network Lifetime Extension CAHAN Architecture

3.2.1 Network Architecture & System Model

QCLE CAHAN is designed to achieve the maximum network lifetime under QoS constraints. QCLE CAHAN will base on the QCMP CAHAN architecture (Chapter 2) and runs a novel QoS-constrained network lifetime extension routing algorithm. QCLE CAHAN has a hybrid architecture that comprises the ad hoc network model and the cellular network model.

To describe the network topology of QCLE CAHAN, we suppose the set of all MTs within the QCLE CAHAN constitute the vertices of a planar graph. An MT that lies within the ad-hoc communication range of another MT is referred to as its neighbor. The ad hoc communication range of MTs in QCLE CAHAN can be regulated and should be less than their maximum ad hoc communication range R_{max} . The required ad hoc

communication range of MTs in QCLE CAHAN will be related to the network lifetime, the total transmitted power consumption, and the average number of hops from source MT to BS. Typically, the ad hoc communication range of MTs is shorter than the communication range of BS (e.g., IEEE 802.11b/IEEE 802.11g, whose maximum communication range is 100m [37]). Therefore, each cell is potentially populated by several ad hoc subnets (AHSs). Each AHS comprises one or more MTs. One AHS may lie on a cell boundary and involve several cells. The topology of AHS can be a tree or a mesh, and it is affected by the ad hoc communication range of each MT in QCLE CAHAN.

We assume that all the problems that cause unidirectional links can be relieved [38], i.e., there exists a bidirectional link between an MT and each of its neighbors. Since all links in an AHS are bi-directional, an AHS is an undirected subgraph of G .

Definition 1- Subnets and Connected MT Set: In an undirected graph $G = (V, E)$ where V is the vertex set of G and E is the edge set of G , assume there are only M subnets X_1, X_2, \dots, X_M where X_i, X_j are disjoint, $i = 1, 2, \dots, M$ and $j = 1, 2, \dots, M$ such that $\bigcup_{i=1}^M X_i = V$.

Moreover, an MT set $X \subset V$ is said to be “connected” if for every pair of MTs in the set X , say MT s and MT d , there exists a path sequence $\langle v_0, v_1, v_2, \dots, v_k \rangle$ such that MT $s = v_0$, MT $d = v_k$, and $(v_{i-1}, v_i) \in E$ for $i = 1, 2, \dots, k$.

The MT set of an undirected AHS is a connected MT set (a connected component) in graph G . Furthermore, the subgraph associated with each AHS is a connected subgraph, in which every MT is reachable from any other MT [39]. In each connected AHS, only some of the MTs are allowed to send data messages directly to its BS in unicast transmission, and these MTs are referred to as the ad-hoc-switch-to-cellular

points (ASCP). However, to have reliable control information, the control packets from the MTs will still be sent directly to BS via cellular system. The ASCP will only relay the uplink data packets from the MTs within the same AHS to the BS; downlink packet will be sent by BS directly to each MT via cellular system. The ASCP is a "gateway" within an AHS. From a graph theoretic point of view, each BS is a vertex in an AHS subgraph that has a link connecting the ASCP to the BS.

3.2.2 QCLE CAHAN Routing Strategy

As mention in Chapter 2, instead of distributing the routing table into each MT and wasting much control message overhead to propagate the route update information to each MT via peer-to-peer communication, we can implement the routing table only in the BS, which is the one-hop neighbor of each MT. Each MT only needs to update the link-cost information to its one-hop neighbor, i.e. BS. The QCLE CAHAN can utilize both centralized and decentralized way for the wireless network construction with the help from a central resource-aware function in the BS. The term resource-aware here means that the BS has the knowledge of current remaining battery energy and needed transmitted power. The central resource-aware function is implemented into each BS. MTs and the BS are cooperating in the system, and control packets to exchange control information during the cooperation are needed. To have reliable control information, all the control packets between BS and MTs are sent via cellular system. All the format of control packet is shown in the Section 2.2.2. The sequence of BS and MT operations in QCLE CAHAN is:

- 1) *MTs broadcast HELLO packets*: Each MT periodically broadcasts a short HELLO packet that includes its ID and the value of the broadcast power to its

neighborhood via common control channel under required ad hoc communication range. The ad hoc communication range of MTs is varied with different broadcast power. The update interval is defined as the time interval between update HELLO packet arrivals. The length of the update interval depends on the mobility of MTs. The optimization of the update interval is needed, and it is discussed in Section 2.5.1.

- 2) *MTs determine remaining battery energy (& radio link cost) and send them to BS:*

The cost of radio link $C_{i,j}$ indicates the needed power from wireless transmitter i to wireless receiver j . The needed power will include transmitted power $P_{i,j}$ required from transmitter i to receiver j and an additional receiver power consumption $P_{j, add}$ of receiver j to devote part of the transceiver to receive and store messages. i.e.,

$$C_{i,j} \equiv P_{i,j} + P_{j, add} . \quad (3.1)$$

After receiving a HELLO packet, a receiver MT j can find the attenuation $\alpha_{i,j}$ according to the received signal strength from neighbor MT i and the broadcast-power information attached in the received HELLO packet. Moreover, the required transmitted power $P_{i,j}$ can be estimated from the attenuation $\alpha_{i,j}$ and the required signal-to-interface ratio (SIR) for data transmission in receiver MT j . The fixed additional receiver power consumption $P_{j, add}$ of receiver j is known by receiver j , and it depends on the transceiver hardware of receiver j . After calculating all one-direction link costs $C_{k,j}$ ($k \in \text{neighbor of } j$), receiver MT j will send modified neighbor-update (NEUP) packet to central BS via cellular system

to update the neighbor ID, link cost, and current MT remaining battery energy information. The modified NEUP control packet is based on the original NEUP control packet in Section 2.2.2 and added into an additional 2-byte current MT remaining battery energy information. The isolated MTs don't need to send the modified NEUP packet. Each modified NEUP control packet has the information of neighbor ID, link cost, and current MT remaining battery energy. All the link cost (& battery energy) information will be sent to the BS such that each BS has a view on the "two-direction" link cost information of the AHS within its individual cell. However, a BS only can get a part of link cost (& battery energy) information of the AHS which lies on the cell boundary. Another part of link cost (& battery energy) information of the AHS on cell boundary must be gotten from its neighbor BS. Getting the link cost (& battery energy) information of AHS from its neighbor BS will be processed only when there is a source MT in the AHS on cell boundary. MSC can help the BSs to get the link-cost information of the AHS on cell boundary, since it has a routing table which stores MT ID, ID of the cell which the MT lies on, and best-relay BS ID. The cell ID of a neighbor MT on cell boundary will indicate which cell has another part of link cost (& battery energy) information of the AHS on cell boundary. Once the BS receives all the link cost (& battery energy) information of the AHS on cell boundary, a new subgraph corresponding to the AHS is constructed.

Modified NEUP (≥ 12 bytes) = {transmitter MT ID, receiver BS ID, NEUP message type, current MT remaining battery energy, # of neighbors, list of neighbor ID and its power cost}

transmitter MT ID 2 bytes	receiver BS ID 2 bytes	NEUP message type 1 byte	remaining battery energy 2 bytes	# of neighbors 1 byte	neighbor ID [I] 2 bytes	power cost [I] 2 bytes	neighbor ID [II] ...
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3) *BS selects ASCPs and finds the minimum-power route from source MT to the ASCPs:* After getting all link-cost information, each BS knows the topology of the AHSs, which include the AHSs on cell boundary and the AHSs within a cell. The BS has a topology table, which stores MT IDs, neighbor IDs, link costs, and current MT remaining battery energy. The BS assigns ASCPs for each AHS based on the information it has. An algorithm for selecting ASCPs will be given in Section 3.3. After selecting the ASCPs, the BS will find a minimum power route from a source MT to its nearest (minimum power cost) ASCP. The BS also can find the minimum power route from a source MT to a destination MT in the same AHS based on the information it has. The searching for minimum power route can be done by using any shortest path algorithm (Dijkstra algorithm or Bellman-Ford algorithm) [66]. However, to the AHS which lies on cell boundary and covers several cells, the algorithms for selecting ASCPs and searching minimum power routes will be processed only in one BS which the source MT belongs to. During the data transmission, the source MT will send the data packet to the ASCP through the minimum power route. Then, the data packet will be relay to the ASCP's own BS. In upstream transmission, the source MT will get the route information (a sequence of relay MT) only from its own BS; the route information is carried by route-update (RUP) packet, which is sent from the BS via cellular system. To route to the destination, each original data packet is encapsulated by preceding it with route information (a sequence of relay MT). The encapsulation is done by the source MT in upstream transmission. In upstream transmission, the BS will decapsulate the data packet and then forwards it to its ultimate destination

like pure cellular networks. Since isolated MTs have directly connection with BS, no encapsulation/decapsulation, RUP packet, and NEUP packet is needed for the isolated MTs, i.e., the isolated MTs will only send out HELLO packet. Moreover, since all downlink packets are sent by BS directly to each MT via cellular system, there is no RUP packet needed in downlink transmission. Once a link breakage (link fail) happen during an update interval, the BS will send an updated RUP packet to the source MT which has a traffic flow through the broken link. Another update RUP is sent to the “link-breakage” router MT which has a connection with the broken link. Therefore, all the packets which stay in the “link-breakage” router MT won't be lost and can be redirected to the destination MT via the new route.

- 4) *Regulating end-to-end hop count to meet QoS constraint:* The data packets for upstream transmissions will be relayed through the ASCPs. However, to meet end-to-end QoS requirement (delay/throughput) or avoid the traffic congestion, the end-to-end hop count should be constrained. In normal operation, the ad hoc communication range is increased and regulated by BS until end-to-end hop count reach its maximum tolerable value or the ad hoc communication range reach its physical maximum value. The BS in upstream transmission can sense the data packet delay and throughput. When end-to-end QoS requirement doesn't be satisfied, the BS can do either way below to find a new constrained route: a) increase the number of ASCPs in an AHS b) decrease the ad hoc communication range of MTs. The relation of end-to-end hop count with the number of ASCPs and the ad hoc communication range of MTs will be described clearly later.

3.3 Energy-Balancing Considerations for CAHAN Network Lifetime Extension

3.3.1 Energy-Balancing Consideration

In the Chapter 2, we consider how to minimize the total transmitted energy consumption of CAHAN. However, in this section, we will consider how to balance the MT battery energies in the network. With only the minimum-power consideration, some MTs may frequently turn out to be the best relay nodes for the minimum-power routes directed to different destination nodes. The selection of the minimum-power route from any optimal minimum-energy routing algorithm could cause “the battery energy-balancing problem” in wireless networks, where some MTs may tend to drain their batteries faster than others. The suitable metric to balance the MT battery energy is to maximize the minimum MT remaining battery energy in the network [68]. As mentioned before, the network lifetime is the time at which an MT with the minimum remaining battery energy drains its battery energy for the first time. Therefore, maximizing the minimum MT remaining battery energy to balance the battery energy will also extend the network lifetime. The transmitted energy of MT battery depends on transmission distance and traffic load, which is the average number of transmitted packets per unit time and is related to the routing tree. Therefore, the traffic load should be considered in balancing the MT battery energy. However, the transmission distance (and routing tree in an AHS) is determined by the MT positions; the MT positions change frequently due to MT mobility. In Section 3.4, it will be shown that increased MT mobility can help to balance the battery energy of MTs better. Here, we only consider the effect of the traffic load on the transmitted energy of MT battery.

3.3.2 QoS Constrained Energy Balancing Problem Formulation & Analysis

A routing tree in an AHS can be constructed by using any routing algorithm; the routing tree is rooted from an ASCP and connects with the source MTs in an AHS.

Definition 2- Traffic Backbone Tree: For a given traffic load set $\lambda = \{\lambda_0, \lambda_1, \dots, \lambda_n\}$ and a connected AHS $\Lambda = (V', E')$, a traffic backbone tree T is defined as

$$T = (V', E'')$$

$$E'' = \{(v_{i-1}, v_i) \in E' \mid \langle v_0, v_1, v_2, \dots, v_k \rangle, v_0 = \text{root}(T), v_k \in \text{Leaf}(T), v_i \in V', i = 1, 2, \dots, k\}$$

where V' denotes the vertex set of Λ , E' denotes the edge set of Λ , E'' denotes the edge set of T , $\langle v_0, v_1, v_2, \dots, v_k \rangle$ denotes a path sequence from v_0 to v_k , $\text{root}(T)$ denotes the root of traffic backbone tree T , and $\text{Leaf}(T)$ denotes a leaf node set of traffic backbone tree T , i.e., a subset of source MTs.

The traffic backbone tree is a rooted tree, where one of its nodes is distinguished from others and is called the root of tree. The subtree rooted at node i is the tree induced by the descendants of node i . The degree of MT i in a traffic backbone tree T is the number of its children. The number of the hops from ASCP to MT i is the depth of MT i . The largest number of the hops from ASCP to leaf nodes (the largest depth of MT in an AHS) is defined as the height of traffic backbone tree T .

Theorem 1- Traffic Load Property of ASCP in a Traffic Backbone Tree: Assume that traffic backbone tree T is a complete k -ary tree in which all leaves have the same depth and all internal nodes have the same degree k . In uplink traffic model, assume that point-to-point traffic starts from one MT in an AHS to BS, and every MT in the AHS is transmitting continuously various packets with the same arrival rate λ to BS via traffic backbone tree T . The total traffic load $TLoad_{\text{head}}$ of the ASCP is

$$TLoad_{head} = \frac{k^{h+1} - 1}{k - 1} \lambda \quad k > 1 \quad (3.2)$$

where h is the height of traffic backbone tree T .

Proof: The number of the tree nodes at any depth d of traffic backbone tree T is k^d .

Therefore, the total number of the nodes of a complete k -ary tree of height h is

$$\begin{aligned} & 1 + k + k^2 + k^3 + \dots + k^{h-1} + k^h \\ &= \sum_{i=0}^h k^i \\ &= \frac{k^{h+1} - 1}{k - 1} \end{aligned}$$

All the MTs in the AHS are transmitting packets with the same arrival rate λ to BS via the

ASCP. Therefore, the total traffic load of the ASCP is $\frac{k^{h+1} - 1}{k - 1} \lambda$.

Corollary 1- Traffic Load Property of any MT in a Traffic Backbone Tree: Assuming the same condition in Theorem 1, the traffic load $TLoad_{MT}$ in internal node i at the depth d of traffic backbone tree T is

$$TLoad_{MT}(d) = \frac{k^{h-d+1} - 1}{k - 1} \lambda \quad k > 1 \quad (3.3)$$

where h is the height of traffic backbone tree T .

Proof: Since each subtree rooted at the internal node i at depth d is the tree induced by the descendants of tree node i , the height of subtree in traffic backbone tree T is equal to

$h - d$. Hence, the traffic load of node i at depth d is $\frac{k^{h-d+1} - 1}{k - 1} \lambda$.

From Theorem 1 and Corollary 1, we can find:

- 1) The traffic load traversing the ASCP is proportional to the function of degree k

with an exponent, which is the height of traffic backbone tree T , i.e., the largest number of the hops from source MT to the ASCP. Therefore, as the size of AHS increases, the traffic load of ASCP in the AHS will also increase.

- 2) Given an AHS, the traffic load in the internal MTs of traffic backbone tree T is inversely proportional to the function of degree k with an exponent, which is the depth from its ASCP, i.e., the traffic load in the internal MTs will have an inversely proportional relation with the number of the hops from the ASCP. In an AHS, the ASCP will have the largest traffic load; the leaf nodes will have the smallest traffic load.

Each AHS in QCLE CAHAN has some ASCPs that are appointed to relay all the information between the nodes in that AHS and the BS. Corollary 1 shows that the traffic load of the ASCP is the largest as compared with the traffic load through any other MT in the same AHS. Therefore, the ASCP and its neighbors tend to drain their batteries faster while other MTs in the leaves of the routing tree remain intact. When the ASCP dies, all the nodes suffer from this failure, so it is imperative to keep the ASCP alive as long as possible. Therefore, we propose an energy-balancing scheme where the ASCP is assigned dynamically based on remaining battery energy constraints. The following gives some metrics that will be useful for further discussion on the topic of energy balancing algorithm.

Metric 1- Metric of Maximizing the Minimum Remaining Battery Energy: Suppose the initial and the remaining battery energy at time t for MT k is $E_{init}(k)$ and $E_r(k,t)$ respectively. Define T_{NL} to be time instance at which the first MT runs out of battery, referred to as the network lifetime. MT j with the minimum remaining battery energy at

time T_{NL} is found as,

$$j = \arg \min_{i=1}^n E_r(i, T_{NL}). \quad (3.4)$$

and the corresponding energy level is denoted as $E_{r,min} = E_r(j, T_{NL})$. The ratio of the remaining battery energy (when the first MT dies) to the initial energy for MT j is expressed as the percentage,

$$\mathfrak{R}_r(j) = \frac{E_r(j, T_{NL})}{E_{init}(j)} \times 100\%. \quad (3.5)$$

The object of metric 1 is to maximize $E_{r,min}$. The $E_{r,min}$ will be increased until all the MT remaining battery energy are equal to one another, i.e., all the MT battery energy in the network are balanced completely. The network lifetime is the time at which an MT j with the minimum remaining battery energy $E_{r,min}$ drains its battery energy for the first time within the entire network. Therefore, maximizing $E_{r,min}$ to balance the MT battery energy in the network will also extend the network lifetime. However, the complete energy balancing, which all the MT has exactly the same remaining battery energy, is difficult to achieve since each MT's battery energy consumption is variable during the network lifetime due to varying transmitted energy consumption of each MT. Moreover, the QoS constraint also has to be considered in extending the network lifetime of QCLE CAHAN.

QoS-Constrained Maximizing Minimum Remaining Battery Energy Problem: For a given source node $s \in V$ and maximum hop count H , find, for each hop count value h , $h \leq H$, and destination node $d \in V$, a hop-constrained energy-balancing route $\zeta = \langle s, v_1, v_2, \dots, d \rangle$ between s and d . i.e.,

$$\begin{aligned} & \text{Maximize } E_{r,min} = E_r(j, T_{NL}). & j = \arg \min_{i=1}^n E_r(i, T_{NL}). \\ & \text{Subject to } 1 \leq h \leq H, & \forall (v_{i-1}, v_i) \in E \end{aligned} \quad (3.6)$$

The ASCP selection scheme in Section 3.3.3 will try to maximize $E_{r,min}$ such that the MT battery energy will be balanced and network lifetime will be extended. The search result of an ASCP depends on the current remaining battery energy and transmitted energy of each MT, which is a function of traffic load and transmitted power. Let $MinEnergyMT$ denote the MT that currently has the minimum remaining battery energy in an AHS. There are three basic concepts to select the ASCPs in order to maximize $E_{r,min}$ and extend the network lifetime. a) Since an ASCP is the root of the routing tree, it has a higher traffic burden, and so a larger energy expenditure than other MTs in the same AHS. Therefore, the ASCP must be chosen from the MTs that have large remaining battery energy. b) Since the traffic load in the internal MTs will have an inversely proportional relation with the number of the hops from the ASCP, the leaf nodes of the routing tree will have the smallest traffic load and less energy expenditure than other MTs in an AHS. To lessen the transmitted energy of $MinEnergyMT$, we should select an ASCP such that the selection can make $MinEnergyMT$ close to leaf nodes of routing tree as much as possible, i.e.. the ASCP should be selected from the MTs which have large number of hop from $MinEnergyMT$. c) The ASCP also have to be the MT which has less uplink transmitted power to the BS in order to save the transmitted energy of the ASCP.

The basic concept to select the ASCPs has described above. Here, we will describe how to decide the number of ASCPs in an AHS to meet the QoS constraint. The number of ASCPs in an AHS will affect the end-to-end QoS between source MT and BS. The average number of hops from source MT to BS in QCLE CAHAN is a function of the number of ASCPs in an AHS (That will be described clearly later).

For an AHS, let's define ASCP-source ratio (ASR) \mathfrak{R}_{ASCP} is the ratio of the number of ASCPs \aleph_{ASCP} in an AHS to the number of the source MTs $\aleph_{s \rightarrow BS}$ which are sending packets to BS in the same AHS, i.e.

$$\mathfrak{R}_{ASCP} = \frac{\aleph_{ASCP}}{\aleph_{s \rightarrow BS}} \quad \aleph_{s \rightarrow BS} \geq 1, \quad 0 < \mathfrak{R}_{ASCP} \leq 1 \quad (3.7)$$

Therefore, given a constant \mathfrak{R}_{ASCP} , the number of ASCPs in each AHS can be determined by the following equation ($\aleph_{s \rightarrow BS}$ is known by BS):

$$\aleph_{ASCP} = \lceil \mathfrak{R}_{ASCP} \aleph_{s \rightarrow BS} \rceil \quad (3.8)$$

$\lceil x \rceil$ denotes the ceiling of x , i.e., the least integer greater than or equal to x .

If the ASR is increasing, the number of ASCPs in an AHS is getting larger and the number of relay MTs is getting less, i.e., less number of hops from source MT to BS. However, the total transmitted power consumption of MTs in uplink is larger and the minimum remaining battery energy can't be maximized. Therefore, the network lifetime will be less. When all MTs in an AHS are source MT, selecting ASR to be 1 will cause all MTs in an AHS are ASCPs and no relay MT can be found in the AHS (the number of the hops between BS and source MT is reduced to one). If this is the case for all AHSs, then the QCLE CAHAN will back to the pure cellular networks. If the ASR is getting small, the number of ASCPs in an AHS is decreasing and the number of relay MTs between source MT and BS is increasing, i.e., larger number of hops from source MT to BS. The total transmitted power consumption of MTs in uplink is less, and the network lifetime of QCLE CAHAN will be longer. The network lifetime of QCLE CAHAN will be increased until the end-to-end hop count reaches its maximum tolerable value. Let

$h_{s \rightarrow BS}$ denote the average number of hops from source MT to BS in QCLE CAHAN. So far, we find that $h_{s \rightarrow BS}$ is a function of both the ASCP-source ratio \mathfrak{R}_{ASCP} and the ad hoc communication range R in network, i.e.,

$$h_{s \rightarrow BS} = f(\mathfrak{R}_{ASCP}, R). \quad (3.9)$$

1) Given a R , the relation between $h_{s \rightarrow BS}$ and \mathfrak{R}_{ASCP} is

$$h_{s \rightarrow BS}(\mathfrak{R}_{ASCP}) \leq h_{s \rightarrow BS}(\mathfrak{R}'_{ASCP}), \quad \text{if } \mathfrak{R}_{ASCP} \geq \mathfrak{R}'_{ASCP} \quad (3.10)$$

2) Given a \mathfrak{R}_{ASCP} , the relation between $h_{s \rightarrow BS}$ and R is

$$h_{s \rightarrow BS}(R) \leq h_{s \rightarrow BS}(R'), \quad \text{if } R \leq R' \quad (3.11)$$

After selecting the ASCPs for maximizing $E_{r,min}$, a set of energy-threshold constraint for the relay MTs between the source MT and the ASCPs can also be used to help to maximize the minimum remaining battery energy. Let the remaining battery energy at time t for MT k denote $E_r(k,t)$, the remaining battery energy threshold of MT k denote δ_k . For a given source node s and destination node d , a threshold constrained energy-balancing route ζ at time t from s to d satisfies the following requirement:

$$E_r(k,t) \geq \delta_k, \quad \forall k \in \zeta \quad (3.12)$$

That is to say, all nodes which have sufficient remaining battery energy (i.e., above a energy threshold δ) will form some possible routes from a source MT to an ASCP. A route with minimum power cost among these routes will be chosen [68]. δ is a energy threshold and range between 0 and MT initial energy E_{init} . δ can be viewed as a protection margin. If some node's remaining battery energy goes below this value, they won't be selected to balance the remaining battery energy. If all the $\delta = 0$, the route between source MT and ASCP is always the minimum-power route. However, an MT

with the minimum remaining battery energy may be selected to be a relay MT and can't conserve its battery energy such that it will drain its battery energy faster. If all the δ of the MTs are close to E_{init} , less relay MT can be found in the network. The total transmitted power consumption of MTs in uplink will be large and the minimum remaining battery energy can't be maximized. Therefore, the energy threshold δ should be adjusted to have longer network lifetime.

For simplicity, we normalize δ by E_{init} . Threshold-initial ratio (TIR) $\mathfrak{R}_\delta(j)$ of MT j is defined as the ratio of the battery energy threshold δ_j to the initial energy $E_{init}(j)$ for MT j , i.e.

$$\mathfrak{R}_\delta(j) = \frac{\delta_j}{E_{init}(j)} \quad E_{init}(j) > 0, \quad 0 \leq \mathfrak{R}_\delta(j) \leq 1 \quad (3.13)$$

Both the threshold-initial ratio (TIR) $\mathfrak{R}_\delta(j)$ and the ASCP-source ratio (ASR) \mathfrak{R}_{ASCP} are two user-defined parameters in the QCLE CAHAN. The TIR and the ASR are used in the QoS-constrained network lifetime extension routing algorithm in QCLE CAHAN (Section 3.3.3).

The QoS constrained network lifetime extension approach will include:

- 1) *ASR limitation network lifetime extension approach*: The data packets for upstream transmissions will be relayed through the ASCPs. As mentioned above, when the ASR is getting small, the number of ASCPs in an AHS is getting less and the hops from source MT to BS is getting large. The total transmitted power consumption of MTs in uplink is less. By decreasing the ASR, maximum network lifetime can be increased until the end-to-end QoS in QCLE CAHAN reaches its maximum tolerable value. The ATEB algorithm in Section 3.3.3 is used to find

the QoS-constrained network lifetime extension route by adjust the ASR. A possible value in decreasing order for ASR can be $1/1, 1/2, 1/3, 1/4, \dots, 1/n$ where $n \in$ positive integer.

- 2) *Proximity limitation network lifetime extension approach*: From a graph theoretic point of view, each BS is a vertex in an undirected graph $G = (V, E)$, and has the link with each ASCP in its cell. The topology of the graph G is affected by the ad hoc communication range of the MTs in QCLE CAHAN. As mentioned above, the maximum number of hops between source MTs and BS in QCLE CAHAN is a monotonically nondecreasing function of the ad hoc communication range of each MT. In normal operation, the ad hoc communication range is increased and regulated by BS until end-to-end hop count reach its maximum tolerable value or the ad hoc communication range reach its physical maximum value. After regulating the ad hoc communication range, a QoS-constrained network lifetime extension route can be found by using the ATEB algorithm in Section 3.3.3.

3.3.3 QoS Constrained Network Lifetime Extension Routing Algorithm

To maximize the network lifetime, different route selection schemes for pure ad hoc network are proposed in [68]. However, none of them considers the QoS issue. On the other hand, the hybrid-overlaid QCLE CAHAN can extend the network lifetime under the end-to-end QoS constraint since the end-to-end hop count in the QCLE CAHAN can be varied by adjusting the ASR or the ad hoc communication range. Therefore, we take this advantage and propose a novel QoS-constrained network lifetime extension routing algorithm for QCLE CAHAN.

Algorithm 1: ASCP-selection Threshold-limitation Energy Balancing Algorithm (ATEB):

ATEB algorithm is a new QoS-constrained network lifetime extension routing algorithm. As mentioned before, ASCP has largest traffic load in a routing tree. In the ATEB algorithm, we avoid selecting the ASCPs from the MTs having less remaining battery energy and limit the minimum-power route only along the relay MTs having sufficient remaining battery energy (i.e., above a energy threshold) in order to maximize $E_{r,min}$ and extend the network lifetime. The ATEB algorithm will be executed after a BS receives all the modified NEUP packets (with remaining-battery-energy information) from MTs.

Let $MinEnergyMT$ denote the MT that currently has the minimum remaining battery energy in an AHS, and $ASCP_{1st}$ denote the first selected ASCP in a subnet. As mentioned before, the ASCPs should be selected from 1) the MTs with large remaining battery energy since an ASCP is the root of the routing tree and has large energy expenditure. 2) the MTs which have large number of hops from $MinEnergyMT$ since it will make $MinEnergyMT$ close to leaf nodes, which have less transmitted energy expenditure. 3) the MTs which have less uplink transmitted power to BS to save their transmitted energy. Therefore, assume there are n MTs in an AHS. The first selected ASCP in the AHS is found as,

$$ASCP_{1st} = \arg \max_{i=1}^n \left\{ E_r(i,t) \cdot \frac{H_i}{P_{up,i}} \right\} \quad (3.14)$$

where $E_r(i,t)$ denotes the remaining battery energy at time t for MT i . H_i denotes the “minimum number of hops” from $MinEnergyMT$ to MT i , and $P_{up,i}$ denotes uplink transmitted power from MT i to BS.

The second selected ASCP will be the MT which has the second large of $\left\{ E_r(i,t) \cdot \frac{H_i}{P_{up,i}} \right\}$. In a word, the k selected ASCP will be the MT which has the k 'st large of

$$\{E_r(i,t) \cdot \frac{H_i}{P_{up,i}}\}.$$

Before describing each step of the ATEB algorithm, we have to give some terminology definitions below:

Definition 3- Articulation MT, Bridges, and Biconnected AHS: In an undirected graph $G = (V, E)$ where V is the vertex set of G and E is the edge set of G , a connected AHS X is said to be a biconnected AHS if for every pair of MTs in AHS X , say $MT\ s \in X$ and $MT\ d \in X$, there exists at least two vertex-disjoint path sequences $\langle v_0, v_1, v_2, \dots, v_k \rangle$ and $\langle u_0, u_1, u_2, \dots, u_k \rangle$ such that $MT\ s = v_0 = u_0$, $MT\ d = v_k = u_k$, $v_i \neq u_j$, $(v_{i-1}, v_i) \in E$, and $(u_{j-1}, u_j) \in E$, for $i, j = 1, 2, \dots, k$. The biconnected AHS exhibits a higher level of connectivity than a connected AHS; if one of the paths connecting two MTs in the biconnected AHS is disconnected, the AHS is still connected. On the other hand, an AHS is not a biconnected AHS if and only if there is one MT whose removal disconnects the AHS. Such an MT is said to be an articulation MT. Similarly, a bridge is one connection (edge) whose removal disconnects the AHS. Obviously, an articulation MT is one of the endpoints of bridge. An articulation MT may connect with one or more bridges, and each bridge connects with a subgraph. The articulation MT may have different number of descendants in the distinct subgraph. A routing tree (traffic backbone tree) in an AHS is rooted at an ASCP and should include all articulation MTs and bridges (if they exist). The articulation MT has to relay the messages from its descendants in the distinct subgraphs to the destination. The transmitted energy consumption of the articulation MT will depend on the number of source MT in its subgraphs and the length of the bridge to the destination.

If $MinEnergyMT$ is an articulation MT, which has descendants in its subgraphs, $MinEnergyMT$ have to relay messages from its descendants to the destination and will not

be a leaf node of routing tree under any selection of ASCP. To determine if $MinEnergyMT$ is an articulation MT, we first remove $MinEnergyMT$ and start traversing the whole AHS by using BFS algorithm. The traversal of the whole AHS can be started at any MT. If $MinEnergyMT$ is not an articulation MT, the number of the searched MTs will be equal to the total number of MTs in the AHS (not including the removed $MinEnergyMT$). That is to say, an MT i is not an articulation MT if and only if

$$\aleph_{travel} = \aleph_{AHS} - 1 \quad (3.15)$$

Otherwise, MT i is an articulation MT.

where \aleph_{travel} denotes the number of the MTs which have been traversed exactly once by using BFS algorithm after removing MT i , and \aleph_{AHS} denotes the total number of MTs in an AHS before removing MT i .

We are ready to describe each step of the ATEB algorithm. As mentioned before, QCLE CAHAN will try to extend the network lifetime only in the uplink transmission since the optimal scheme for the network lifetime in the downlink transmission is just one-hop transmission directly from BS. To extend the network lifetime in uplink transmission, the ATEB algorithm consists of the following steps (The flow diagram for ATEB algorithm is shown in Figure 3.3):

- 1) *Determining each AHS*: As mentioned in Section 3.2.2, each modified NEUP control packet has the information of neighbor ID, link cost, and current MT remaining battery energy. All the link cost information is sent to the BS via modified NEUP packet such that the BS has a view on the “two-direction” link cost. The planar graph $G = (V, E)$ corresponding to the set of all MTs within a cell and on the cell boundary will be constructed after the BS receive all the modified

NEUP packet and the link cost information from its neighbor BS, where V is the vertex set of G and E is the edge set of G . The breadth-first search (BFS) algorithm can be used to determine each AHS in the planar graph G . The BFS algorithm is one of the simple algorithms for searching a graph [39]. The traversal of the whole graph G could be started at any vertex. BFS algorithm picks any vertex in an AHS and systematically explores the edges of graph G to discover the vertices until every MT in the same AHS is discovered. After determining an AHS, BFS algorithm will pick another un-discovered vertex and continuously discovers the other MTs in different AHS. Therefore, traversing the whole planar graph G with BFS algorithm can determine each AHS and find which AHS an MT belongs to. Several AHS subgraphs may exist in the whole graph G , and each MT may belong to different AHS.

- 2) *Discovering MinEnergyMT in each AHS*: During traversing the planar graph G to determine each AHS, the *MinEnergyMT* in each individual AHS can be also found. The work is done by comparing all the current MT remaining battery energy in the same AHS, and the *MinEnergyMT* will be the MT that currently has the minimum remaining battery energy in the AHS ³.
- 3) *Recording all MinEnergyMTs into array LowerBatteryList[l]*: All the *MinEnergyMTs* found in each AHS will be recorded into an array *LowerBatteryList[l]*. That will be useful for following Step 7 to maximize $E_{r,min}$. Array *LowerBatteryList[l]* will record all the MTs that have been a *MinEnergyMT* in the past, i.e.,

³ If more than one MTs have the same minimum remaining battery energy in an AHS, the MT which has larger uplink transmitted power to BS will be picked to be the *MinEnergyMT*.

$LowerBatteryList[l] \leftarrow LowerBatteryList[l] \cup \{MinEnergyMTs\}$

- 4) *Deciding the number of ASCPs under the QoS constraint:* Since the average number of hops from source MT to BS in QCLE CAHAN is a function of the ASR, the ASR should be adjusted to meet the end-to-end QoS constraint. The number of ASCPs \aleph_{ASCP} in an AHS can be decided from equation (3.8), i.e.,

$$\aleph_{ASCP} = \lceil \mathfrak{R}_{ASCP} \cdot \aleph_{s \rightarrow BS} \rceil. \quad \aleph_{s \rightarrow BS} \geq 1, \quad 0 < \mathfrak{R}_{ASCP} \leq 1$$

where \mathfrak{R}_{ASCP} denotes the ASR and $\aleph_{s \rightarrow BS}$ denotes the number of the source MTs which are sending packets to BS in the same AHS. The $\aleph_{s \rightarrow BS}$ is known by the BS. While the \mathfrak{R}_{ASCP} is decreasing, the \aleph_{ASCP} is decreasing and the network lifetime is increasing. However, the number of hops from source MT to BS is increasing. The maximum network lifetime can be increased until the end-to-end QoS in QCLE CAHAN reaches its maximum tolerable value. A possible value in decreasing order for \mathfrak{R}_{ASCP} can be $1/1, 1/2, 1/3, 1/4, \dots, 1/n$ where $n \in$ positive integer.

- 5) *Selecting the ASCPs from an AHS:* Assume there are n MTs in an AHS. The first selected ASCP in the AHS is found as (3.14),

$$ASCP_{1st} = \arg \max_{i=1}^n \left\{ E_r(i, t) \cdot \frac{H_i}{P_{up, i}} \right\}$$

where $E_r(i, t)$ denotes the remaining battery energy at time t for MT i . H_i denotes the “minimum number of hops” from *MinEnergyMT* to MT i , and $P_{up, i}$ denotes uplink transmitted power from MT i to BS. The k selected ASCP will be the MT which has the k 'st large of $\left\{ E_r(i, t) \cdot \frac{H_i}{P_{up, i}} \right\}$. This selection will make

MinEnergyMT far away the root of routing tree such that it close to leaf nodes of the routing tree. The ASCP also will have large remaining battery energy $E_r(i,t)$ and less uplink transmitted power $P_{up,i}$.

- 6) *Sorting the array LowerBatteryList[l]*: After adding all new *MinEnergyMTs* into array *LowerBatteryList[l]*, we sort the sequence of all the elements in *LowerBatteryList[l]* by using a sorting algorithm. The sorting algorithm will arrange the sequence of all the elements in *LowerBatteryList[l]* in increasing order, i.e., the MT which has the i th smallest remaining battery energy will be in the i th element of *LowerBatteryList[l]*.
- 7) *Meeting the Energy Threshold Limitation*: Start to check array *LowerBatteryList[l]* from its first element, which has the smallest remaining battery energy. If there exists a nonarticulation MT j where $j \in \text{LowerBatteryList}[l]$ & $j \notin \text{ASCP set}$ such that $E_r(j,t) < \text{battery energy threshold } \delta_j$, all the links between the nonarticulation MT j and its neighbors will be cut off except the least-cost link in order to make j become a leaf node. However, under any circumstance, any connection between an articulation MT and its neighbor can't be cut off since it will partition its AHS into two or more AHSs. The energy threshold limitation is shown in (3.12), i.e., remaining battery energy $E_r(k,t) \geq \text{battery energy threshold } \delta_k, \forall k \in \text{route } \zeta$ & $0 \leq \delta_k \leq \text{initial energy } E_{init}$. To have longer network lifetime, the δ_j will be varied by adjusting the \mathfrak{R}_δ in (3.13), i.e., TIR $\mathfrak{R}_\delta(j) = \frac{\delta_j}{E_{init}(j)}$, $E_{init}(j) > 0$, $0 \leq \mathfrak{R}_\delta(j) \leq 1$. If $\mathfrak{R}_\delta \rightarrow 0$, then $\delta_j \rightarrow 0$ the route between source MT and ASCP is always the minimum-power route.

However, an MT with the minimum remaining battery energy may be selected to be a relay MT and can't conserve its battery energy. If all the $\mathfrak{R}_s \rightarrow 1$, then $\delta_j \rightarrow E_{init}$ and few relay MT is found in the network and the minimum remaining battery energy can't be maximized.

- 8) *Finding the minimum-power route from source MT to ASCP*: The final step is finding a route that has minimum power from the source MT to one of the ASCPs. The minimum power route between the source MT and the ASCP can be found by using any shortest path algorithm such as Dijkstra algorithm or Bellman-Ford algorithm [66]. The Dijkstra algorithm requires that all link costs are nonnegative. In the worst case its computational complexity is $O(N^2)$, comparing with the worst-case estimate $O(N^3)$ of the Bellman-Ford algorithm. The worst-case computational requirements of the Dijkstra algorithm are considerably less than those of the Bellman-Ford algorithm. Therefore, the Dijkstra algorithm is more suitable for dense networks, as compared with Bellman-Ford algorithm. The final route from source MT to BS via ASCP is shown in Figure 3.2. The route between source MT and ASCP is a threshold-constrained minimum-power route.

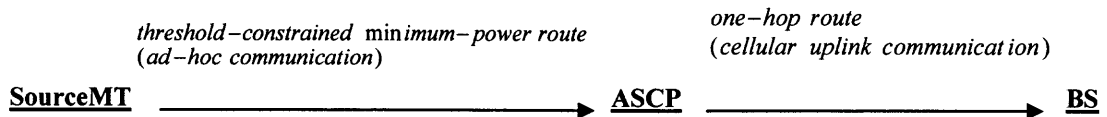


Figure 3.2 The final route from source MT to BS via ASCP.

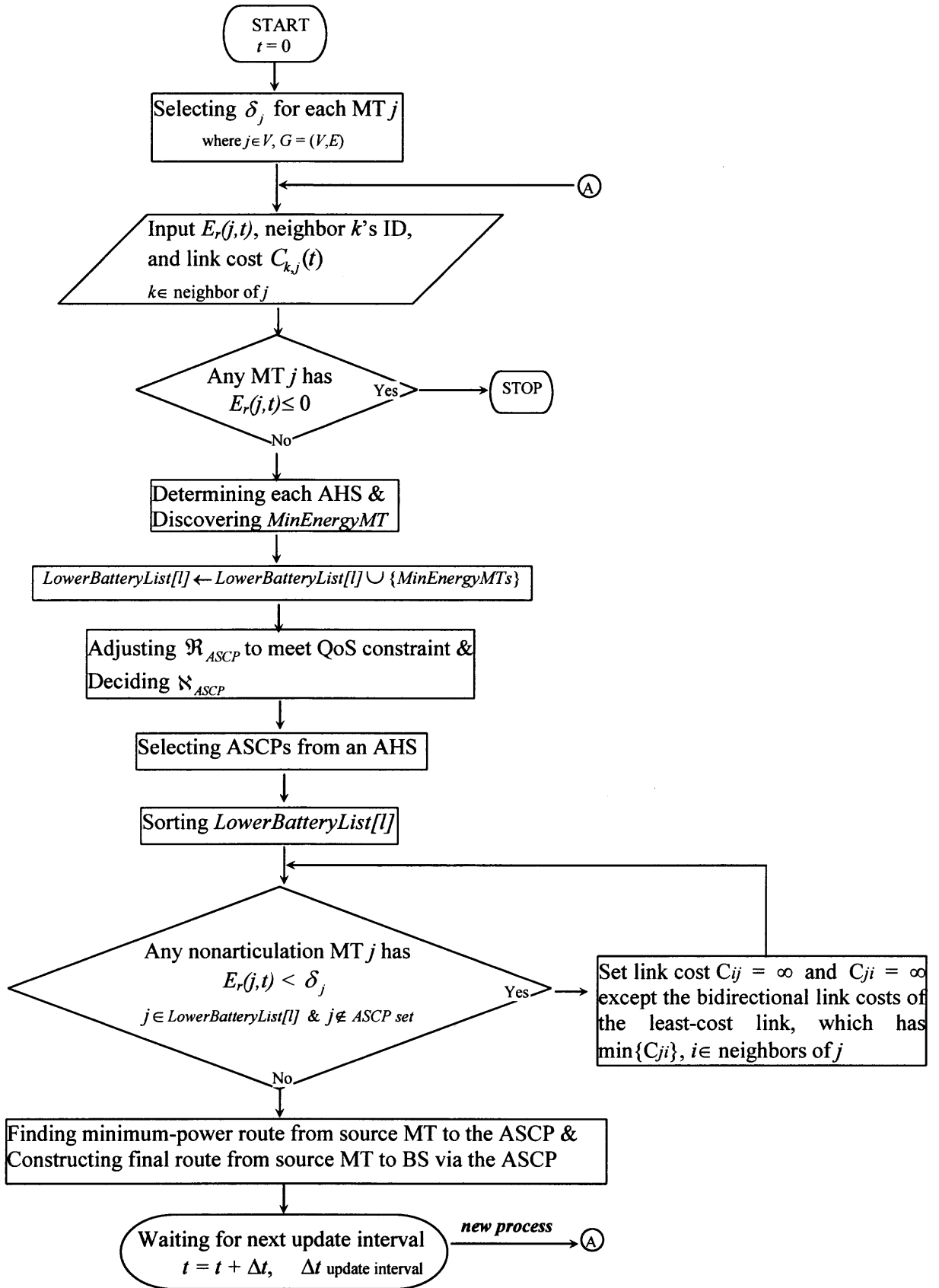


Figure 3.3 Flow diagram for ATEB algorithm.

3.4 Performance Evaluation & Numerical Study

3.4.1 Simulation Model

The simulation model of QCLE CAHAN was implemented using OPNET (Figure 3.4). In the simulation, the initial coordinates of all MTs are generated from an i.i.d. uniform distribution over 7 cells. The QoS constrained ATEB algorithm in BS determines the ASCPs and the network-lifetime-extension route. All the functions in QCLE CAHAN system model were implemented inside MTs, BSs, and MSC. All of BSs were connected with the same MSC. The simulation has capability to simulate a network with hundreds of MTs.

- 1) *Mobility model*: In each small update interval, the MTs' velocities are constant, and the magnitude component of the velocity is uniformly randomly selected from interval $[0, V_{max}]$, where V_{max} is the maximum moving speed of an MT and is related to the MT mobility. The direction component of the velocity is uniformly distributed in the interval $[0, 360]$ degrees, where "360" is the maximum degree of a circle. The mobility of MTs is restricted within 7 cells.
- 2) *Traffic model*: Two different traffic models are individually used in our uplink traffic simulations and downlink traffic simulations. In uplink traffic simulations, every MT is a source that is sending messages, and all the traffic flows in the network have destinations outside the MSC range and traverse through the MSC. In downlink traffic simulations of QCLE CAHAN, to save the MT battery energy, every MT is a destination MT that is directly receiving data messages from the BS via one-hop cellular system. In each traffic model, there is only the point-to point traffic, i.e., a packet has only one destination. Moreover, in each uplink/downlink

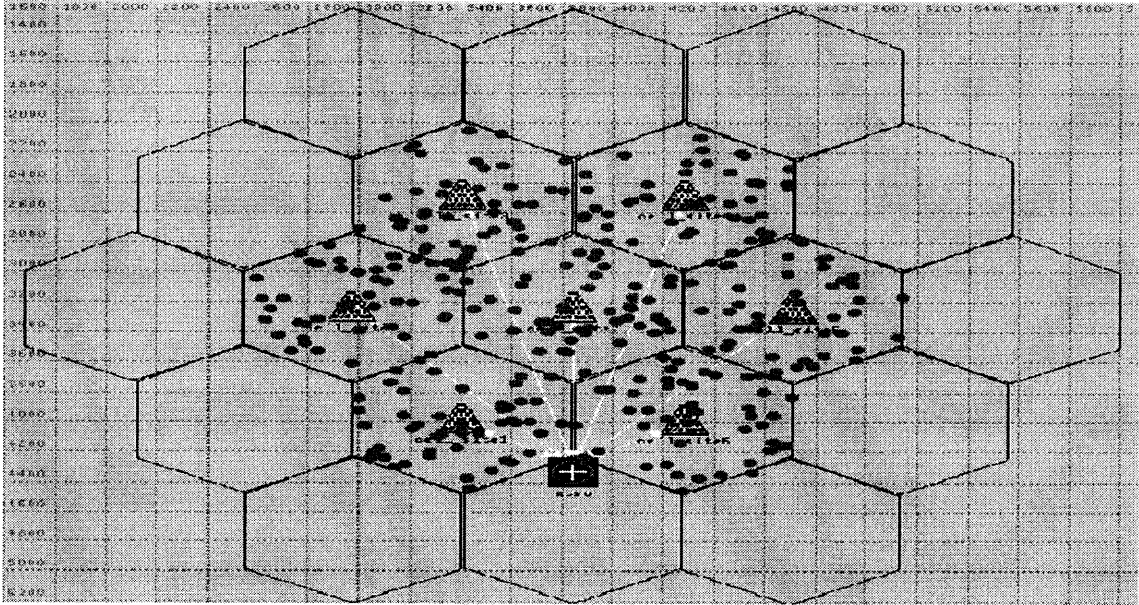


Figure 3.4 OPNET simulation model.

simulation update interval, each source/destination MT sends/receives exactly two 1250-byte data packets (Each packet has the same length).

Simulation Data Packet Format

QCLE CAHAN needs to encapsulate (precede) each original data packet (1250 bytes) with an additional route information (a sequence of relay MTs).

Original data packet pattern (1250 bytes)

type of services 1 byte	total length (bytes) 2 bytes	message type 1 byte	source ID 2 bytes	destination ID 2 bytes	data 1242 bytes
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The attached route information (≥ 1 bytes) in each original data packet

# of relay MTs 1 bytes	relay MT ID [I] 2 bytes	relay MT ID [II]
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- 3) *Channel model*: The channel attenuation is expressed as a function of distance with a path loss exponent, lognormal random variable representing shadowing, and complex zero-mean Gaussian random variable representing Rayleigh fading. We assume the fading is slow and the fast closed loop power control is available to combat the fading [52] and perfectly tracks the fading channel with no delay.

The fast closed loop power control can be implemented in the forward and the reverse directions. The bi-directional closed loop power control can be found in both CDMA2000 system and W-CDMA system [53-54].

- 4) *Power consumption model*: The minimum power allocation scheme is implemented in both cellular system and ad hoc system. We assume all MTs have the same transceiver hardware. The whole power consumption of MT transceiver hardware includes transmitted power, transceiver power, and processing power. The transmitted power refers to the power radiated by the antenna, and the transceiver power refers to the power consumed by the transceiver circuits. However, in the design of modern processors, the processing power consumption required for processing and computation can be made negligible as compared with the transmitted power and the transceiver power in recent low-power processor design [32]. The transceiver power consumption can be modeled as a basic fixed transceiver power consumption (80 mW) consumed at each MT and an additional receiver power consumption (20 mW) to devote part of the transceiver to receive and store messages [32]. This additional receiver power consumption is only added in the power consumption of the MTs that receive the transmission.

In the simulations, the transceiver power consumption, which refers to the power consumed by the transceiver circuits, affects MT battery energy and network lifetime. However, the transceiver power consumption will not be considered during the comparison of transmitted power consumption between CAHAN and pure cellular networks since the transceiver power doesn't affect the interference of CDMA systems. In

a word, we only consider the transmitted power while comparing the interference of CDMA systems. While comparing the MT remaining battery energy or the network lifetime of CDMA networks, we will consider their transmitted power and transceiver power.

The simulations were run for a range of network density. Here, the network density is defined as the average number of MTs being served in a cell site. For each network density, we record the network lifetime and calculate the total transmitted energy in an update interval. As mentioned above, in each simulation update interval, each source MT will sent just two same-size 1250-byte data packets. In j update interval of uplink simulation, the total transmitted energy consumption E_j^T after each source MT sending just two same-size data packets is defined as below.

$$E_j^T = \sum_{i=1}^K E_i^t . \quad (3.16)$$

where E_i^t denotes the transmitted energy consumption of two same-size data packets from a source MT i to BS along a sequence of relay MTs. K denotes the total number of the source MTs in uplink transmission.

To make smooth simulation results curve on a figure, we repeat the same update interval for whole network lifetime and take their average. The final simulation results are shown in following subsection. The comparison criterions for QCLE CAHAN and pure cellular networks are: a) Assume that there is no noise. b) Each MT has the same transceiver hardware and QoS requirement. c) There is no packet loss. In our simulations, transmission quality E_b/I_0 is set to meet QoS requirement $\gamma'_{i,v}$. The simulation parameters are shown in Table 3.1.

Table 3.1 QCLE CAHAN Simulation Parameters

Parameters	
Simulation region	7 cells
Diagonal of each hexagonal cell	1000m
Path loss exponent	4
Transmitter antenna gain	1
Receiver antenna gain	1
Maximum communication range (R_{max})	BS : 500m MT: 100m
Transmission Bandwidth (B.W.)	Between BS and MT: 5MHz Between two MTs: 5MHz
Transmission quality E_b/I_0	$\frac{E_b}{I_0} = \gamma'_{i,v}$ ^a

^a $\gamma'_{i,v}$ denotes the QoS requirement from BS v to an MT i , E_b denotes the bit energy, and I_0 denotes total interference density. The transmission quality E_b/I_0 should greater or equal to $\gamma'_{i,v}$. If taking $E_b/I_0 = \gamma'_{i,v}$, it will spend the minimum transmitted power to satisfy the QoS requirement [46].

3.4.2 Simulation Results, Observation, and Discussion

1) *ASR limitation network lifetime extension simulations*: The network lifetime of pure cellular networks and QCLE CAHAN (with three different ASR) in uplink traffic simulation is shown in Figure 3.5. The maximum network density that can be supported in pure cellular networks is 50. The range of the network density in our simulation is from 36 to 44 (per a cell), so the total number of MTs in our 7-cell simulation model is from 252 to 308. The maximum MT moving speed in Figure 3.5 is high (up to 30 m/sec). Figure 3.5 shows the relation between the network lifetime and the ASR of the QCLE CAHAN. When the ASR is getting small, the number of ASCPs in an AHS is getting less and the number of relay MTs is getting larger, i.e., larger number of hops from source MT to BS. Therefore, the total transmitted power consumption of MTs in uplink is less, and the network lifetime of QCLE CAHAN is longer. By decreasing the ASR, maximum

network lifetime can be increased until the end-to-end QoS in QCLE CAHAN reaches its maximum tolerable value. The QCLE CAHAN network lifetime is extended as compared to the case of pure cellular networks, especially in the case of high network density. The increase in network lifetime is high in the case of high network density since the total transmitted energy consumption of pure cellular networks at high network density is larger.

The transmitted energy in Figure 3.5.b is the average total transmitted energy of the update intervals in network lifetime. The total transmitted energy consumption will include all the transmitted energy consumption for the data message and control message (Chapter 2). The simulation results show that QCLE CAHAN (with three varied ASR) spends less total transmitted energy than pure cellular networks for each network density. This behavior arises as a result of several reasons.

First, we consider the transmitted energy of QCLE CAHAN and pure cellular networks at a certain network density and a fixed ASR. The total transmitted power of cellular networks can be reduced as a result of multihopping in CAHAN since messages will be forwarded via relay MTs which split the longer transmission distance between two communicating points into two or more short transmission distances. That is one reason why the total transmitted energy of QCLE CAHAN is less than the total transmitted energy of pure cellular networks.

Secondly, for the same value of network density, we compare the total transmitted energy of QCLE CAHAN with the total transmitted energy of pure cellular networks for three different ASR ($1/2$, $1/4$, and $1/8$). As the ASR is decreased, the number of ASCPs in an AHS is getting less. As a result more relay MTs from source MT to BS can be found,

and thus the total transmitted power in QCLE CAHAN will be decreased. Using QCLE CAHAN results in significant savings in total transmitted energy as the ASR is decreased.

Thirdly, for a fixed ASR, the advantage of QCLE CAHAN is more evident when network density is greater. High network density means more MTs of pure cellular networks are serviced in a cell and its needs more transmitted power. However, when the network density is greater in QCLE CAHAN, more relay MTs from source MT to BS can also be found. That is the reason why the total transmitted energy of QCLE CAHAN is proportional to network density with a gentler gradient than the total transmitted energy of pure cellular networks. Therefore, a dense cell in QCLE CAHAN will save more transmitted energy in general.

On the other hand, the transmitted power of a transmitter MT in CDMA system is proportional to the transmission distance and the network density [46]. As the network density is increased, the interference increases. The network capacity of CDMA system is interference limited. When pure cellular network reach its maximum network density that can be supported, the QCLE CAHAN still can allow more MTs to enter its cells.

Figure 3.5.c shows the relation between ASR and the maximum number of hops from source MT to BS within the largest AHS in QCLE CAHAN. The hop count in Figure 3.5.c is the average of the hop count over all the update intervals in network lifetime. As the ASR is decreased, the number of hops from source MT to BS will be increased. The ASR in QCLE CAHAN should be decreased until the end-to-end delay reaches maximum tolerable value, and the network lifetime of QCLE CAHAN will reach its maximum possible value. When the ASR of QCLE CAHAN is 1, QCLE CAHAN will

become a pure cellular network (since each MT is a source MT in our simulation) and the number of the hops between BS and MTs will be one.

2) *Proximity limitation network lifetime extension simulations*: The network lifetime of pure cellular networks and QCLE CAHAN (with three different ad hoc communication ranges) in uplink traffic simulation is shown in Figure 3.6. Figure 3.6.a shows the relation between the network lifetime and the ad hoc communication range of MT in the QCLE CAHAN. As the ad hoc communication range of each MT is increased, more relay MTs from source MT to BS can be found and hence number of hops from source MT to BS will be increased. Therefore, the total transmitted power consumption of MTs in uplink is less, and the network lifetime of QCLE CAHAN is longer. The QCLE CAHAN network lifetime is extended as compared to the case of pure cellular networks, especially in the case of high network density. The transmitted energy in Figure 3.6.b is the average total transmitted energy of the update intervals in network lifetime. The total transmitted energy consumption will include all the transmitted energy consumption for the data message and control message (Chapter 2).

Figure 3.6.c shows the relation between ad hoc communication range and the maximum number of hops from source MT to BS within the largest AHS in QCLE CAHAN. The hop count in Figure 3.6.c is the average of the hop count over all update intervals in network lifetime. As the ad hoc communication range of each MT is increased, the number of hops from source MT to BS will be increased. There is a trade-off between network lifetime and end-to-end delay (i.e., the number of hops between BS and MTs). The ad hoc communication range of each MT in QCLE CAHAN can be increased until the end-to-end delay reaches maximum tolerable value, and the network

lifetime of QCLE CAHAN will reach its maximum possible value. When all the ad hoc communication ranges of MTs in QCLE CAHAN are zero, QCLE CAHAN will become a pure cellular network and the number of the hops between BS and MTs will be one.

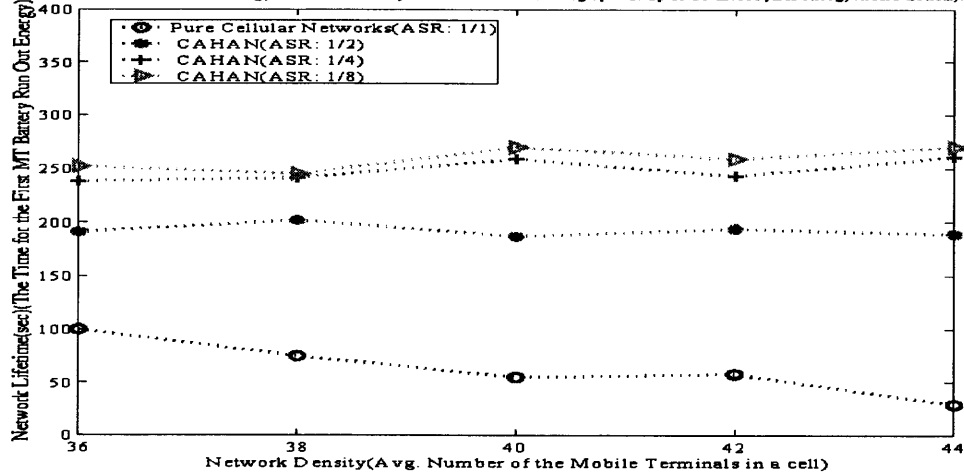
3) *Comparison of QCLE CAHAN and QCMP CAHAN*: The object of the QCLE CAHAN is to maximize the network lifetime. Figure 3.7.a shows that QCLE CAHAN with the ATEB algorithm certainly has much longer network lifetime than the QCMP CAHAN. The MT moving speed in Figure 3.7 is low (pedestrian speed 0.3 m/sec). On other hand, in Figure 3.7.b, the QCMP CAHAN has the optimal minimum total transmitted power since the QCMP CAHAN uses the shortest path algorithm to find the minimum-power route (Chapter 2). The transmitted energy in Figure 3.7.b is the average total transmitted energy of the update intervals in network lifetime. The total transmitted energy consumption will include all the transmitted energy consumption for the data message and control message (Chapter 2). In the comparison simulation, the ASR of the QCLE CAHAN is adjusted until it has the same QoS constraint with the QCMP CAHAN, i.e., the same maximum number of hops from source MT to BS (Figure 3.7.c). At that QoS constraint, the ASR of the QCLE CAHAN is equal to 1/8 (Figure 3.7). The ATEB algorithm dynamically selects ASCPs according to the MT remaining battery energy and maximizes the minimum remaining battery energy $E_{r,min}$. Therefore, it balances all the MT battery energy and maximizes its network lifetime. The ATEB algorithm has the satisfactory and desired qualities in extending the network lifetime. But, some MTs in the QCMP CAHAN (with shortest path algorithm) may frequently turn out to be the best relay nodes for the minimum-power routes from source MT to BS. Especially, in the QCMP CAHAN (with shortest path algorithm), once an MT is selected

to be the root of a routing tree in uplink transmission, it tends to continuously be the root of the routing tree (or the neighbor of a root) in a certain period, especially in lower MT mobility.

4) *Relation of the network lifetime with the MT mobility:* In this subsection, we will show that the network lifetime of QCLE CAHAN also can be extended in higher MT mobility, termed mobility effect. Figure 3.8 shows that high MT mobility can extend the network lifetime of QCLE CAHAN. As mentioned before, the transmitted energy of battery in each MT depends on transmission distance and traffic load, which is related to routing tree in an AHS. The transmission distance and the routing tree are determined by all MT positions; the MT positions change frequently and affected by MT mobility. When MT mobility is high, the routing tree in each AHS will be changed more frequently; the traffic load and the transmitted energy of battery in each MT will be balanced. Therefore, the network lifetime of QCLE CAHAN will be extended.

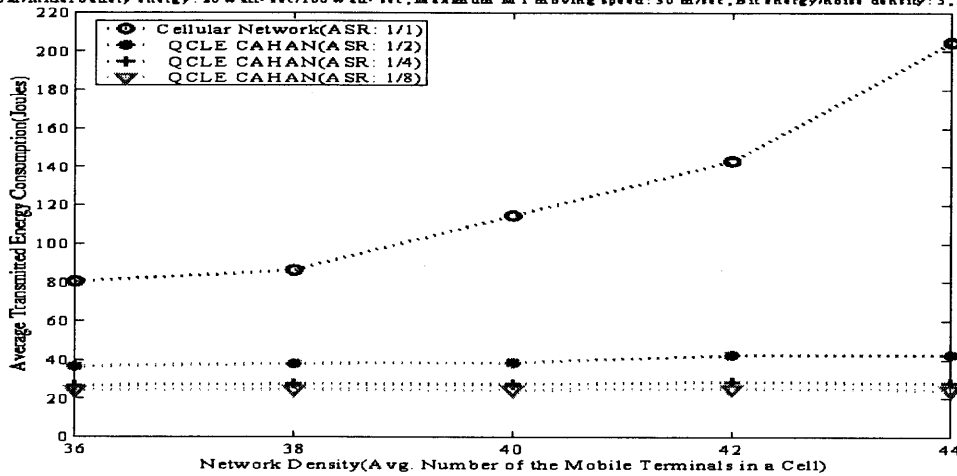
5) *Control message energy/channel bandwidth consumption:* Figure 3.9 shows the energy consumption of HELLO/NEUP/RUP control packets in QCLE CAHAN, and Figure 3.10 shows energy consumption of RTS/CTS/ESR/ESA control packets in QCLE CAHAN. The control message energy consumption in Figure 3.9 and Figure 3.10 are small and have been counted into the total transmitted energy in Figure 3.5, Figure 3.6, and Figure 3.7. Figure 3.11 shows the HELLO/NEUP/RUP control channel bandwidth consumption in QCLE CAHAN. As comparing with total number of data message bits received in the destinations during data transmission (Figure 3.12), the control channel bandwidth consumption of the HELLO/NEUP/RUP packet are much less.

The Network Lifetime of the QCLE CAHAN(Ad hoc communication range: 100m, Threshold/Initial battery energy: 20Watt-sec/100Watt-sec, additional receiver/basic transceiver energy: 20mW/80mW, Maximum MT moving speed: up to 30 m/sec, Bit energy/noise density: 3, Interval: 1



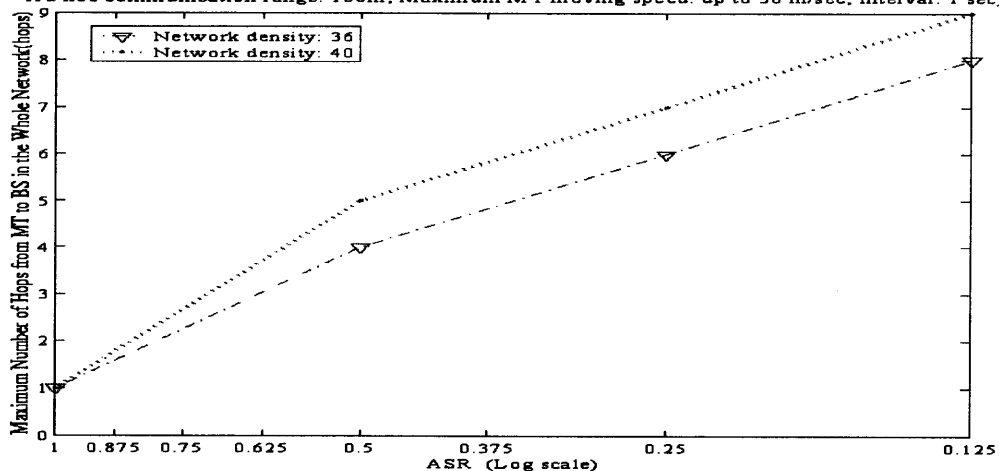
(a)

Total Data Packet + Control Packet Energy Consumption of Cellular Networks/ QCLE CAHAN(Uplink, Ad hoc communication range: 100 m, Threshold/Initial battery energy: 20Watt-sec/100Watt-sec, Maximum MT moving speed: 30 m/sec, Bit energy/noise density: 3, Interval: 1 sec)



(b)

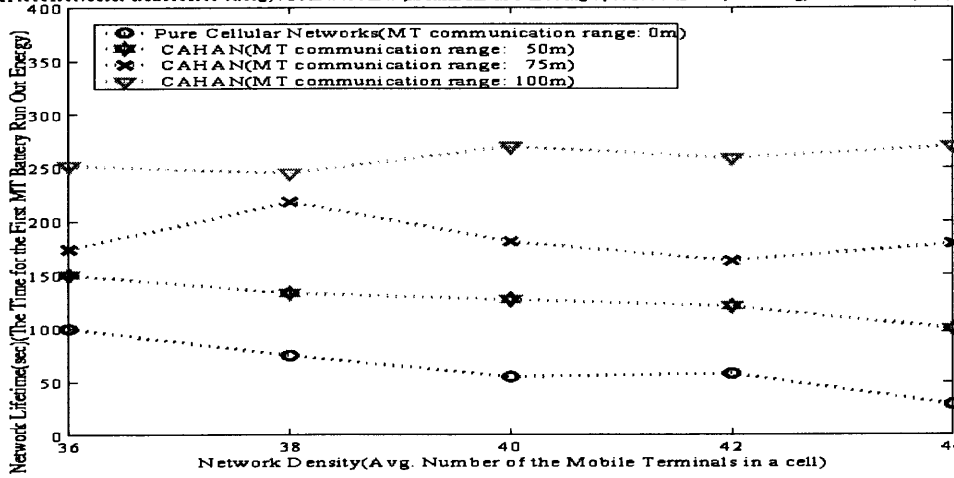
The Maximum Number of Hops from source MT to BS in the Whole Network of QCLE CAHAN(Uplink simulation, Ad hoc communication range: 100m, Maximum MT moving speed: up to 30 m/sec, Interval: 1 sec)



(c)

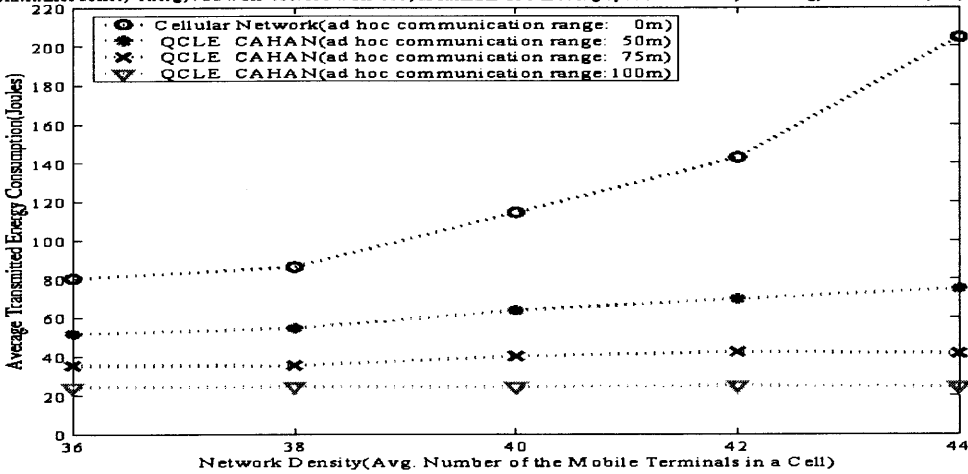
Figure 3.5 QCLE CAHAN with various ASR in uplink traffic simulation (a) Network lifetime of QCLE CAHAN, (b) Total data packet and control packet energy consumption, (c) Maximum number of hops from MT to BS in QCLE CAHAN.

The Network Lifetime of the QCLE CAHAN(ASR: 1/8, Threshold/initial battery energy: 20Watt. sec/100Watt. sec, additional transmitter/basic transceiver energy: 20mW/80mW, Maximum MT moving speed: 30 m/sec, Bit energy/noise density: 5, Interval: 1 sec)



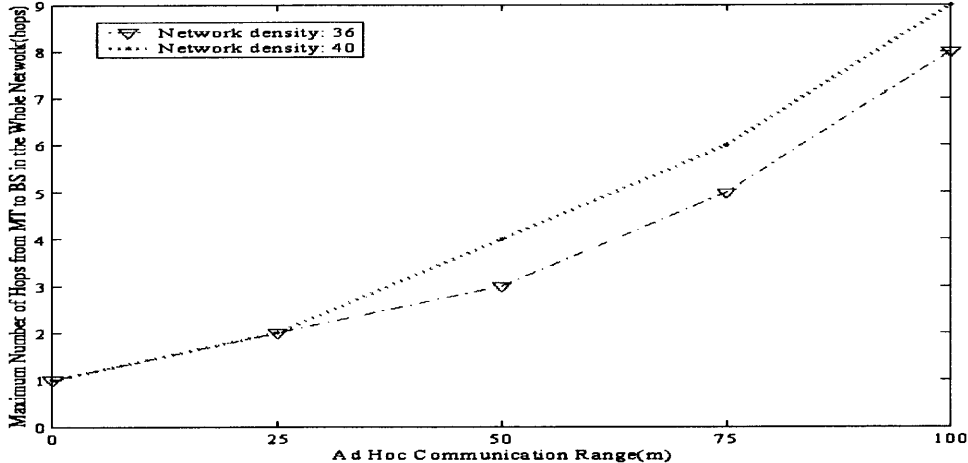
(a)

Total Data Packet & Control Packet Energy Consumption of Cellular Networks vs. QCLE CAHAN(Uplink simulation, ASR: 1/8, Threshold/initial battery energy: 20Watt. sec/100Watt. sec, Maximum MT moving speed: 30 m/sec, Bit energy/noise density: 5, Interval: 1 sec)



(b)

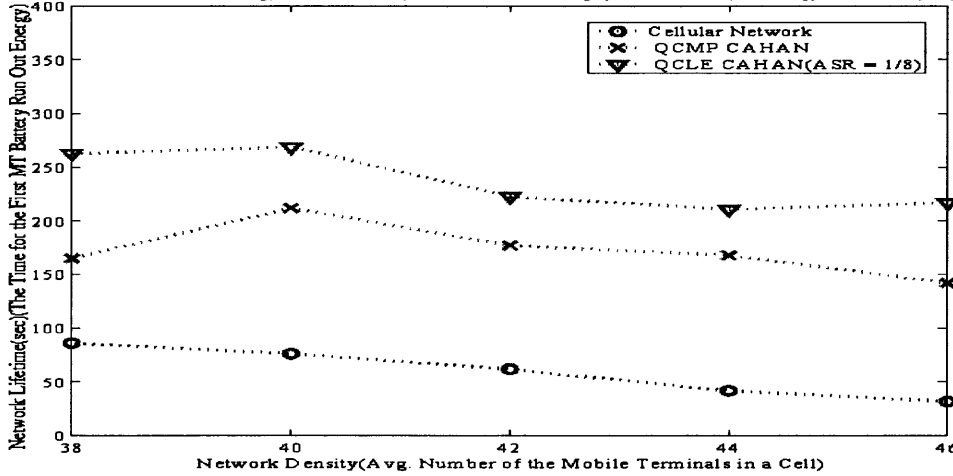
The Maximum Number of Hops from source MT to BS in the Whole Network of QCLE CAHAN(Uplink simulation, Ad hoc communication range: 100m, Maximum MT moving speed: up to 30 m/sec, Interval: 1 sec)



(c)

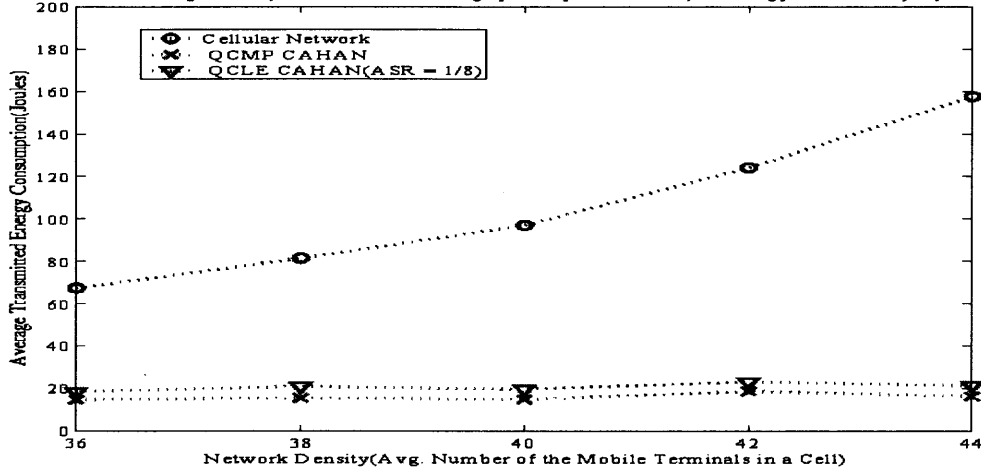
Figure 3.6 QCLE CAHAN with various ad hoc communication range in uplink traffic simulation (a) Network lifetime of QCLE CAHAN, (b) Total data packet and control packet energy consumption, (c) Maximum number of hops from MT to BS in CAHAN.

Network Lifetime of Cellular Network/CAHAN(ad hoc communication range: 100m, Threshold/Initial battery energy: 20 Watt-sec/100 Watt-sec additional receiver/basic transceiver energy: 30m W/80m W, Maximum MT moving speed: 0.3 m/sec, Bit energy/noise density: 5, Interval: 1 sec)



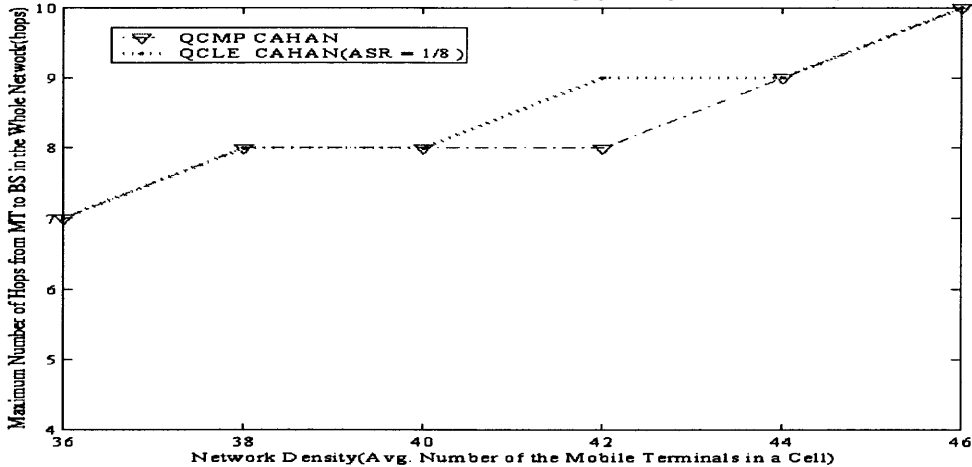
(a)

Total Data Packet & Control Packet Energy Consumption of Cellular Networks/CAHAN (Uplink simulation, Ad hoc communication range: 100m, Maximum MT moving speed: up to 0.3 m/sec, Bit energy/noise density: 5, Interval: 1 sec)



(b)

The Maximum Number of Hops from source MT to BS in the Whole Network of QCLE CAHAN(Uplink simulation, Ad hoc communication range: 100m, Maximum MT moving speed: up to 0.3 m/sec, Update Interval: 1 sec)



(c)

Figure 3.7 QCLE CAHAN, QCMP CAHAN, and cellular networks in uplink traffic simulation (a) Network lifetime, (b) Total data packet and control packet energy consumption, (c) Maximum number of hops from MT to BS in CAHAN.

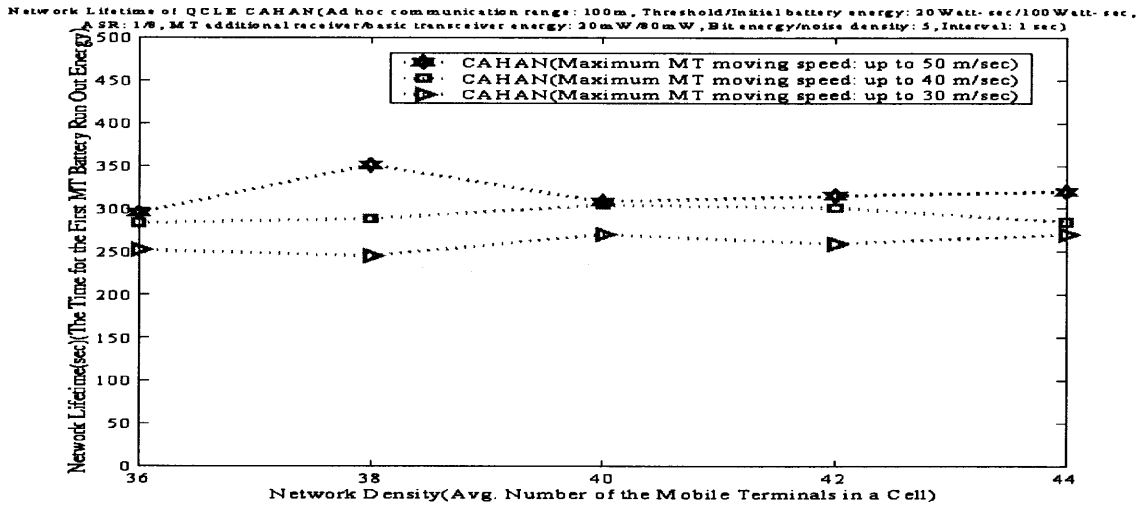
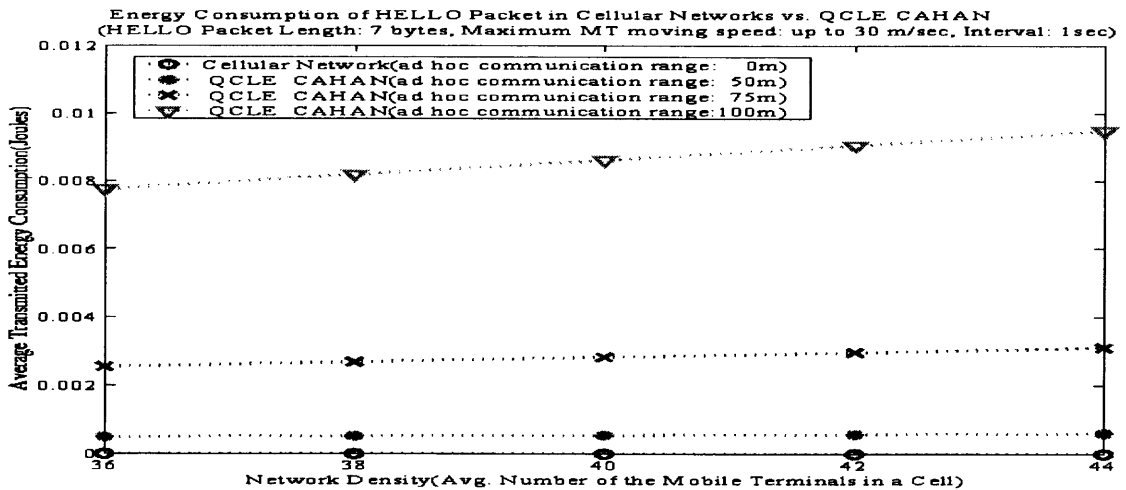
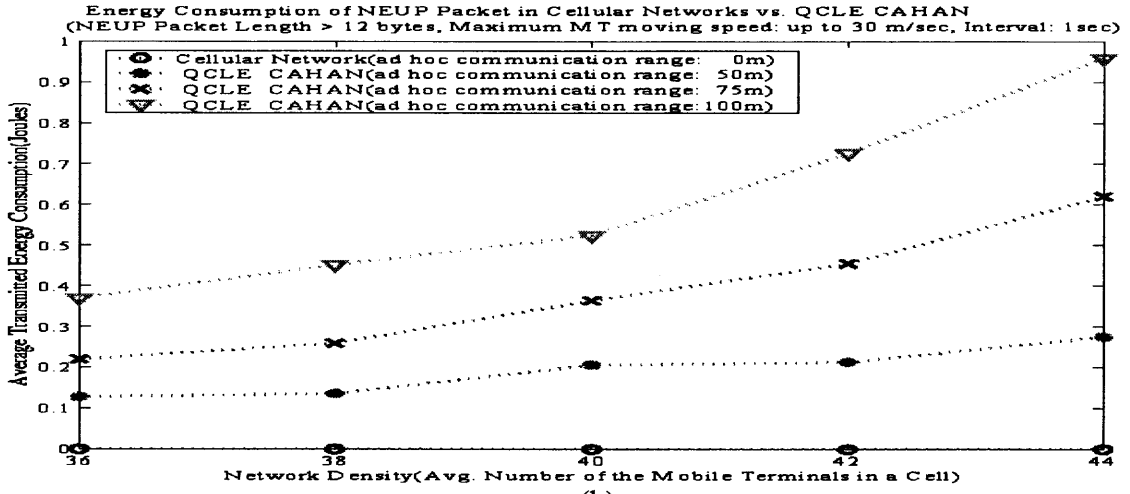


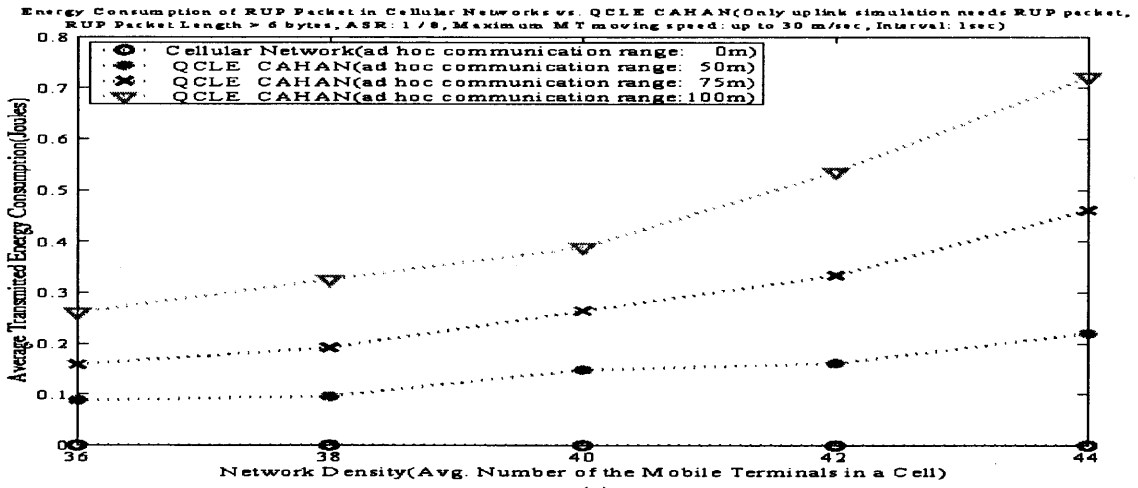
Figure 3.8 Relation between QCLE CAHAN network lifetime and the MT mobility (uplink traffic simulation).



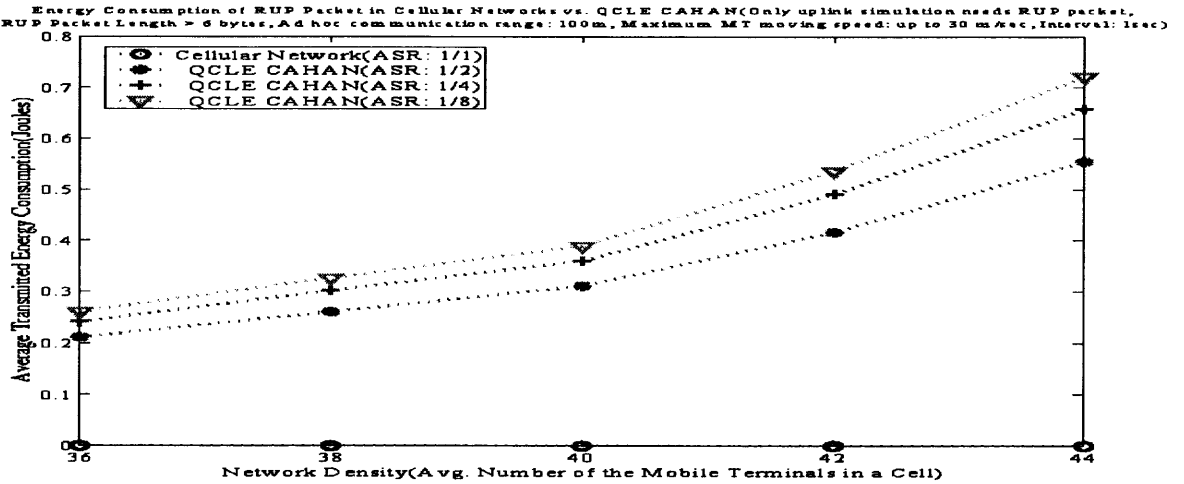
(a)



(b)



(c)



(d)

Figure 3.9 Energy consumption of HELLO/NEUP/RUP control packets for system maintenance in QCLE CAHAN: (a) HELLO packets, (b) NEUP packets, (c) RUP packets with various ad hoc communication range, (d) RUP packets with various ASR (RUP packets are needed only if there are source MTs in networks, i.e., RUP packets are needed only in uplink simulation).

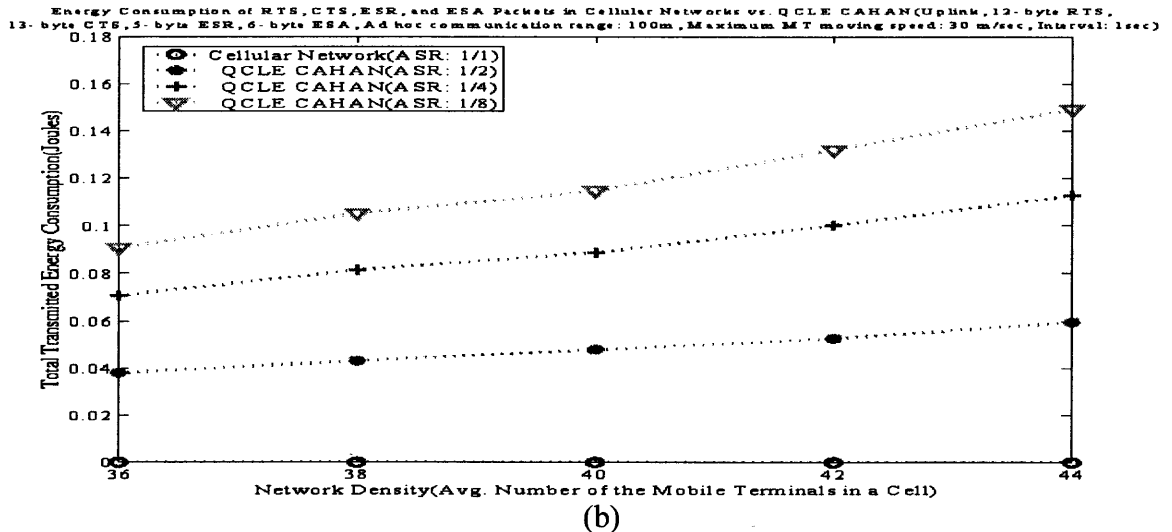
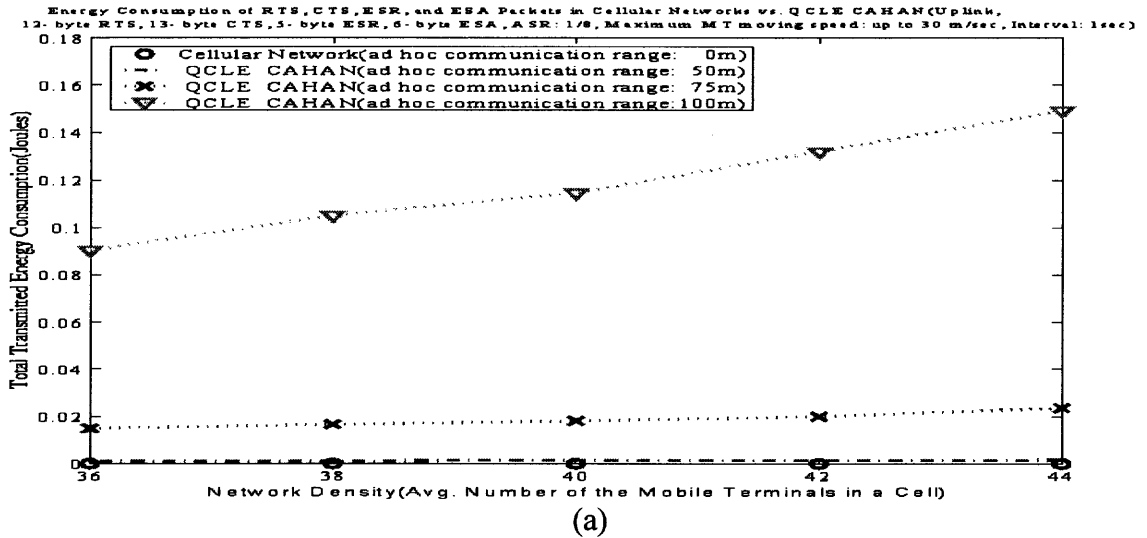
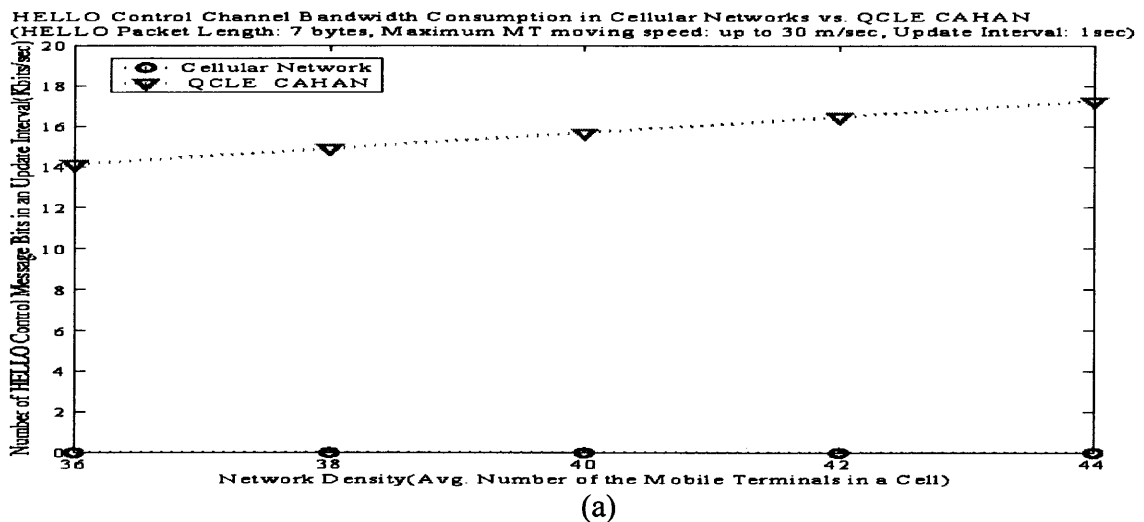
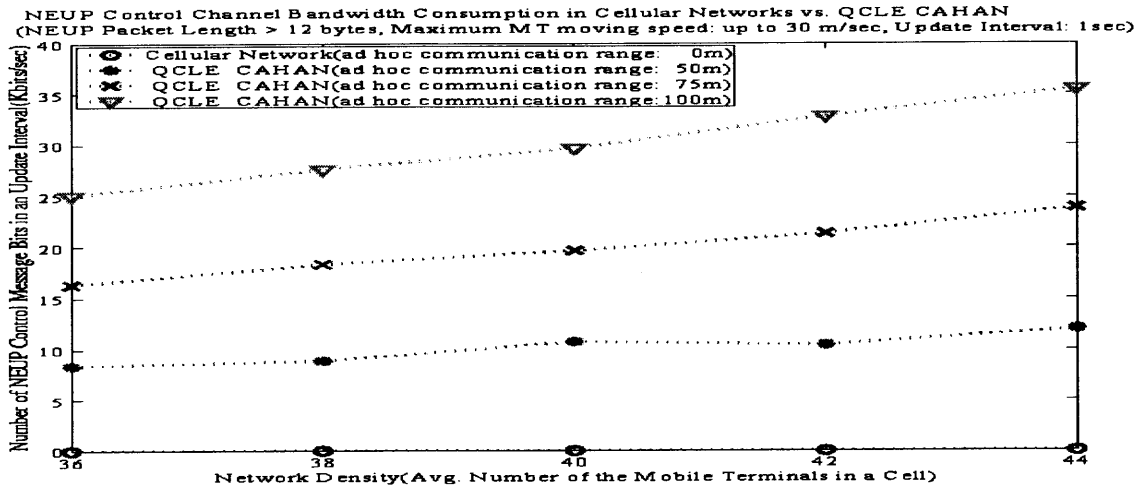
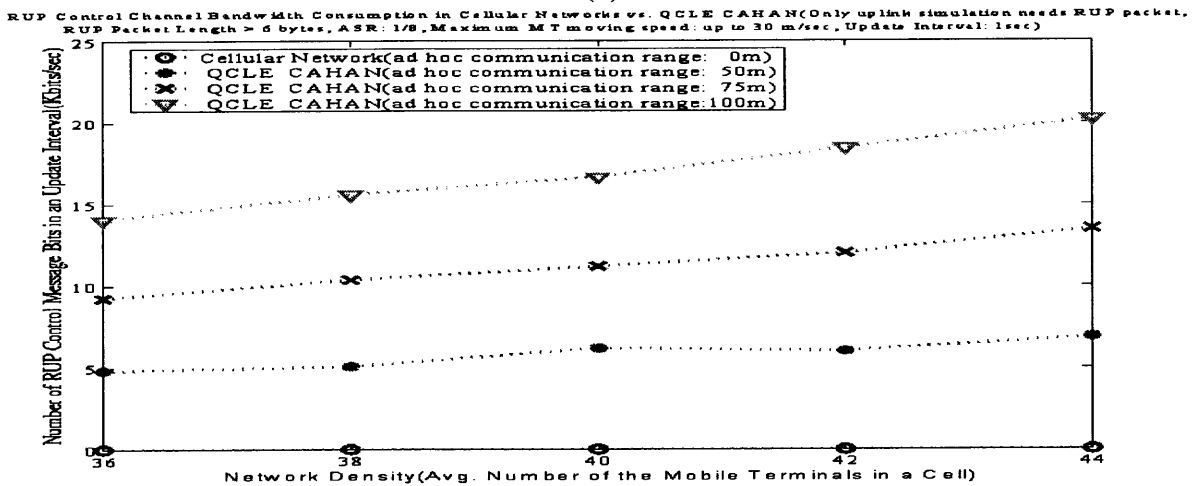


Figure 3.10 Energy consumption of RTS/CTS/ESR/ESA control packets for peer-to-peer data transmission in QCLE CAHAN: (a) Various ad hoc communication range, (b) Various ASR.

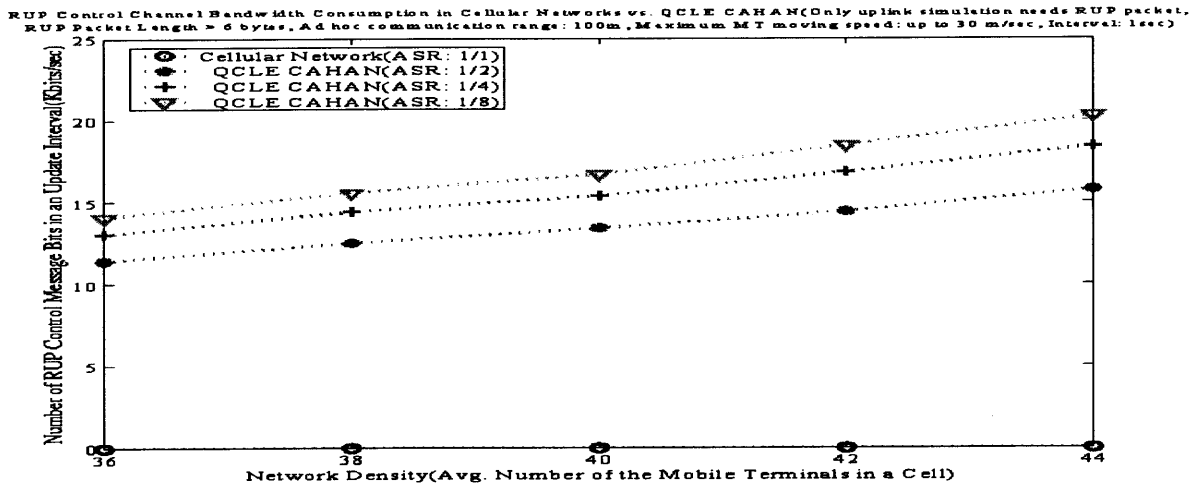




(b)



(c)



(d)

Figure 3.11 HELLO/NEUP/RUP control channel bandwidth consumption for system maintenance in QCLE CAHAN: (a) HELLO packets, (b) NEUP packets, (c) RUP packets with various ad hoc communication, (d) RUP packets with various ASR (RUP packets are needed only if there are source MTs in networks, i.e., RUP packets are needed only in uplink simulation).

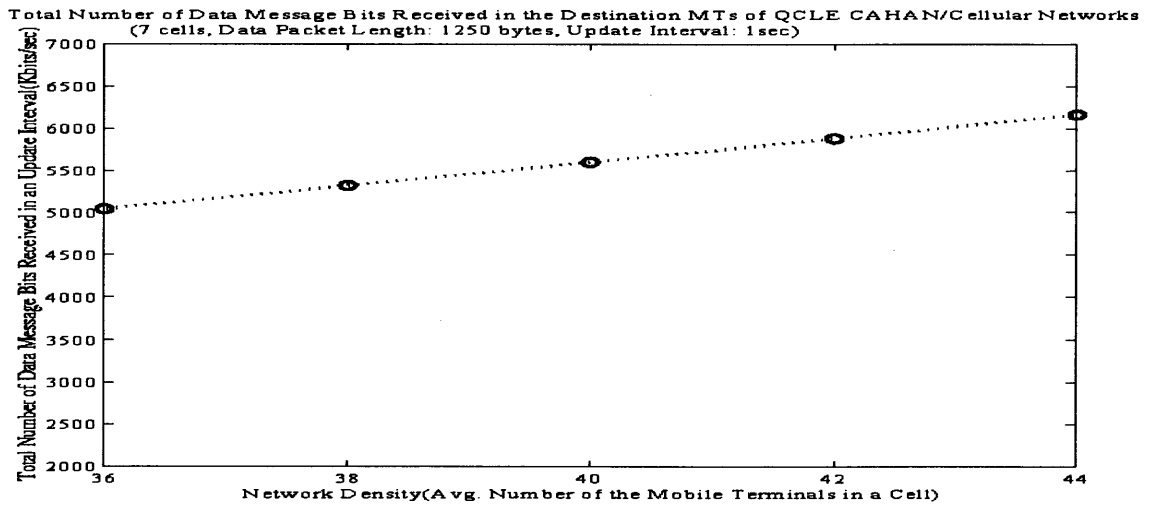


Figure 3.12 Total number of data message bits received in the destinations of QCLE CAHAN/cellular networks in an update interval.

CHAPTER 4

GEOCASTING IN GEOLOCATION-AWARE CELLULAR AD HOC AUGMENTED NETWORK ARCHITECTURE

4.1 Introduction

Recently, providing multicast services in wireless networks is becoming popular. Multicasting is the mechanism to transmit the same messages to a selected group of destinations (multiple destinations). Furthermore, the scope of the applications that are well suited for multicasting is growing. The current maturity of the Internet and a growing necessity in the integration of cellular services and the Internet will make delivering location-specific information to the mobile terminals (MTs) within a given geographic area possible [62-63]. An MT's "current coordinates" will be fashionable information as "current time". Our vision of future wireless systems is one that will present a competitive edge over wired systems by exploiting the very nature of the network, i.e., providing location-dependent services.

Geocasting, which is one of the location-dependent services, is the mechanism to multicast messages to the network nodes whose physical locations lie within a given geographic area, termed the target area. The geocasting concept can be deployed in all networks. However, the architecture of wireless network has a defining effect on the geocasting mechanism. Geocasting in single-hop cellular networks, where there are fixed network access points, presents a different set of problems than geocasting in ad hoc networks, where there is no network infrastructure.

Some of the possible new applications for the geocasting will be [62-63]:

1. Sending important/emergency messages selectively only to a specific area: the messages can be sent to everyone in a specific area, such as a train station, highway, or building. The message could be the area-specific weather forecasts, traffic reports, or conference (meeting) messages.
2. Advertising and providing a given service only to clients who are within a certain geographic range from server: a business might want to advertise/provide a given commercial service only to clients within a certain geographic range, say, within two miles of the company's store. The providing service could be any entertainment applications.
3. Finding out resource which is currently present in a specific geographic area: users could use geographic message to locate resources/services within a geographic region in their direct proximity. The resource/service could be a restaurant, gas station, or library.

While initially the GPS (Global Positioning System) was mainly for military applications and its commercial use was prohibitively expensive, the recent rapid and massive commercialization of GPS applications have made inexpensive low-power small-size implementations possible such as a *12mW low-power* CMOS GPS receiver or a *3.6 mm² -area 35-mW small-size* GPS receiver [25-28]. A fully operational GPS system consists of 24 satellites located in six orbital planes at a height about 20000 km. Each satellite broadcast a signal consisting of a 50-bps navigation data stream with a coarse acquisition code (C/A-code) on L1 frequency (1575.42 MHz) or a precision code (P-code) on L2 frequency (1227.6 MHz) [28-30]. The GPS signal format is known as direct sequence spread spectrum. The navigation data contain the satellite clock and orbital

parameters that are used in the computation of user position. A receiver can calculate its own position and speed by correlating the signal delays from any four satellites [28]. To meet the FCC E911 requirements, many companies have proposed the highly integrated versatile GPS receiver for the cellular handset. For example: 1) gpsOne technology, which is proposed by QUALCOMM Inc. [20]. 2) A highly integrated GPS receiver from Texas Instruments Inc. [21]. 3) STORM RFIC GPS receiver from Conexant Systems Inc. [22] 4) assisted-GPS (A-GPS) [7]. The A-GPS location technology has been specified by 3GPP and 3GPP2 (APPENDIX C). A-GPS's accuracy of under 20 m is a very reasonable expectation in 67 percent of calls [2]. The A-GPS have the advantages [6-7]: 1) Inexpensive: A-GPS terminals are expected to incorporate geolocation functions at the chip level which therefore might be made for only a few dollars per handset more than conventional terminals. The network-side equipment promises to be much less costly than alternative approaches. 2) Applicable to all air interface. 3) differential GPS (DGPS) level of accuracy. 4) Locations available in buildings and other heavily-faded situations. 5) Little or no new hardware needed in BSs, and no new connections between network elements. 6) Rapid acquisition time. Moreover, another hybrid approaches can be used, e.g., the combination of A-GPS and observed time difference of arrival (OTDOA) [2]. To meet the FCC E-911 accuracy requirements, Qualcomm have produced MSM5100 third-generation CDMA handset, which has the GPS position location capable [20]. The MSM5100 use the hybrid location approach that combines measurements from GPS and forward/reverse links of a CDMA system to improve position service availability. This technology has been extensively tested and deployed in Japan. The MSM5100 will also enable a broad range of future 3G GPS-related services, including commercial tracking

services, navigation information, area-specific weather/traffic reports, and a broad range of entertainment applications. Therefore, to meet the FCC E911 requirements, the GPS receiver will be a "necessary" and a part of cellular handset.

A cost-effective low-power small-size GPS receiver will be implemented into our proposed geolocation-aware cellular ad hoc augmented network (GA CAHAN) (Figure 4.1) for next generation wireless networks. The GPS receiver can be used not only to help the location-based applications such as E911 and geocasting, but also to help the synchronization, the resource management, and the mobility management. Moreover, by using A-GPS approach or other hybrid location approach (that combines measurements from GPS and forward/reverse links of a CDMA system), the limitations of indoor/shadowed environments, cost-effective problem, and packaging problem can be overcome. The position service availability also can be improved (APPENDIX C).

In a wireless network model, power consumption is a critical design criterion. A wireless network model that minimizes power consumption is highly desirable. In conventional cellular networks, the BSs involved in geocast service will use their maximum broadcast power to send messages to the MTs in a target area. Especially, when the target area is on a cell boundary and covers several cells, all the BSs involved in geocast service have to geocast the same messages to the target area such that it will spend much total transmitted energy. The major contribution of this work is the proposed GA CAHAN architecture (Figure 4.1) that is designed to achieve the minimum total transmitted power of geocast service under delay constraints. The less total transmitted power on the air will also cause less interference in CDMA cellular systems. GA CAHAN is an evolutionary approach to cellular networks. GA CAHAN has a hybrid

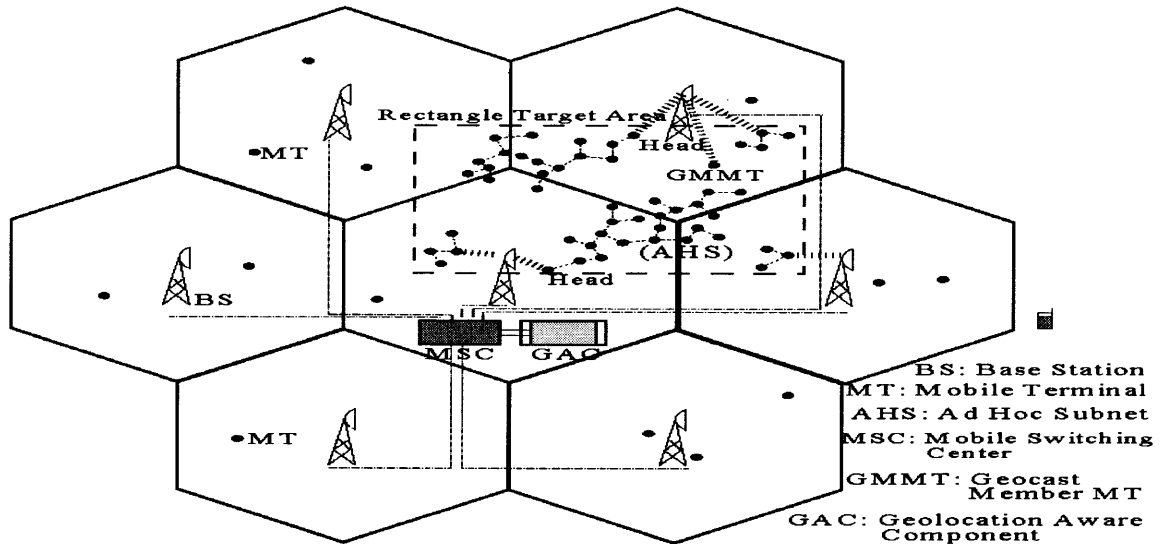


Figure 4.1 GA CAHAN architecture for geocast service.

architecture, in which each MT of CDMA cellular networks has ad hoc communication capability. The MT in GA CAHAN can relay the geocast messages to save total transmitted power in the system. However, the saving in the total transmitted power does not come free. Due to the increased number of hops involved in information delivery from BS to destination, the end-to-end delay increases. On the other hand, based on the sensitivity to delay, the geocast applications will be classed as: high delay-sensitivity geocast service, medium delay-sensitivity geocast service, and low delay-sensitivity geocast service. When the geocast service are high delay sensitivity, the MTs in target area of GA CAHAN will not relay any messages and the GA CAHAN will reduce to the traditional cellular network, i.e., cellular networks are a special case of GA CAHAN. When the delay sensitivity of the geocast service is medium or low, the MTs in target area of GA CAHAN will relay the geocast messages to save the total transmitted power in system. GA CAHAN has ability to adapt to various delay constraints for different geocast service.

When the delay sensitivity of the geocast service is low, we also propose a simple

less-power path search scheme that can further reduce the total geocast energy in GA CAHAN. We assume that certain latency of the geocast messages is tolerated. We show that in geocasting, the total transmitted energy consumed by the MTs and BSs is lower in the case of GA CAHAN than in the case of pure cellular networks. When the size of geocast target area is large, GA CAHAN can save larger transmitted energy. The advantage of GA CAHAN is more evident when a target area is on a cell boundary and covers several cells. When the number of cells covered by the target area is increased, GA CAHAN can save larger transmitted energy. Moreover, in GA CAHAN, energy savings in a dense target area is higher. In GA CAHAN, each MT in the target area forwards same message “only once” and spends just little MT battery energy. The large total energy saving means that it not only avoid power outage problem, but also can make company provide cheap service (or less monthly basic service fee) for MT users. The MTs in the target area not only can get their needed geocast message, but also can get other benefits (cheap service and less monthly basic service fee), so they would be happy to cooperate with BS (or other MT) to forward the geocast message to its neighbor.

4.2 Geocast Architecture and System Model

4.2.1 GA CAHAN Architecture for Geocast Service

GA CAHAN has a hybrid architecture that comprises the ad hoc network model and the cellular network model. However, in geocast service, we only allow the MT whose physical location lies within a given geographic area (target area) to activate its ad hoc communication system, and such an MT is named geocast member mobile terminal (GMMT). We assume that the GMMTs are interested in the geocast messages, i.e., they

want the geocast messages. As mentioned before, in the geocast service, the GMMTs can get the needed geocast messages (or obtain other benefits), so they are happy to forward the geocast messages to their neighbors. Since the position of each MT changes constantly, we also assume that a continuous GPS feed is available. We also assume that there is no error in coordinate measurement. The instantaneous coordinates of each MT can be accurately found by self-geolocation via GPS feed [32]. The recent low-power small-size implementation of a GPS receiver [25-30] [32] makes its presence a viable option in wireless network design. The MT GPS receiver only picks up the broadcast radio signal from different satellites and estimates its position, no other communication with GPS needed. Before GA CAHAN is implemented, the wireless resource consumption for the broadcasted satellite signal already existed for the wireless applications of other wireless systems. The MT GPS receiver in GA CAHAN only receives signal such that it will not spend any extra message overhead and radio resource (channel bandwidth and transmitted power). It only needs to spend an additional receiver power consumption to receive/store the signal and a process power to process the signal from satellite. Moreover, the process power consumption and the additional GPS receiver power consumption for receiving the GPS signal is very small in recent low-power GPS receiver design [25-30] [32].

1) *Ad hoc network model of GA CAHAN*: Several ad hoc subnets (AHSs) may exist within a geocast target area. Each AHS comprises one or more GMMTs. One AHS may lie on a cell boundary and involve several cells. The topology of AHS can be a tree or a mesh, and it is affected by the ad hoc communication range of each GMMT. In the ad hoc network model of GA CAHAN, peer-to-peer transmissions may involve several

router GMMTs, in which packets are relayed in the same frequency band. For this peer-to-peer model, we use a multirate CDMA protocol with request-to-send/clear-to-send bandwidth reservation mechanism as the medium access technique [33]. Each GMMT is assigned one spreading code. We assume that there are always a sufficient number of spreading codes that can be assigned to GMMTs. The request-to-send (RTS) and clear-to-send (CTS) message dialogue can solve the “hidden-terminal” problem. We assume that all the links in an AHS are bidirectional links.

To describe the network topology of GA CAHAN, we suppose the set of all GMMTs within the GA CAHAN constitute the vertices of a planar graph.

Definition 1- Neighbor, Nonneighbor, and Neighborhood: Neighbor N_i , nonneighbor \bar{N}_i , and neighborhood NH_i of an MT i are defined to be

$$N_i = \{j \in V \mid d_{ij} \leq R_i, j \neq i\}$$

$$\bar{N}_i = \{j \in V \mid d_{ij} > R_i, j \neq i\}$$

$$NH_i = \{(x, y) \mid d_{i \rightarrow (x,y)} \leq R_{max}\}$$

where V denotes the vertex set of a planar graph G , d_{ij} denotes the distance between MT i and MT j , (x,y) denotes the coordinates of an MT, $d_{i \rightarrow (x,y)}$ denotes the distance between MT i and (x,y) , R_i denotes the ad hoc communication range of MT i , and R_{max} denotes the maximum ad hoc communication range of MT i , which is determined by the physical power limitations of MT i .

Suppose the set of all GMMTs within a target area constitute the vertices of a planar graph G . There exists a bidirectional link between a GMMT and each of its neighbors. A GMMT that lies within the ad-hoc communication range of another GMMT is referred to as its neighbor (Figure 4.2). Since all links in an AHS are bi-directional, an

AHS is an undirected subgraph of G . Furthermore, the subgraph associated with each AHS is a connected graph, in which every GMMT is reachable from any other GMMT [39]. In each connected AHS, only one of the GMMTs is allowed to receive geocast messages directly from its BS, and this GMMT is referred to as the AHS Head (The control packets from the MTs will still be sent directly to BS via cellular system). That is to say, the AHS Head is a "gateway" within an AHS. From a graph theoretic point of view, each BS is a vertex in an AHS subgraph that has only one link connecting the BS to the AHS Head.

2) *Cellular network model of GA CAHAN*: For the cellular network model of GA CAHAN, two distinct frequency bands between BS and AHS Heads are used separately to carry the information on the upstream and the downstream. The multirate CDMA is the medium access technique between the BS and the AHS Heads [46].

4.2.2 Geocast Session Setup & Geocast Routing Strategy

The geocast sender has graphic user interface capability, and the boundaries of the target area are simply drawn onto a map. To request a geocast service, the sender first sends the information of target area boundary (with delay-sensitivity level) to the geolocation-aware component (GAC), which has a view of the cellular layout (cellular boundaries) (Figure 4.1). The GAC is a separate network box in GA CAHAN architecture and is reached via mobile switching center (MSC). The information of target area boundary is represented as a single closed polygon whose vertices are denoted by geographic coordinates. The information of target area boundary is relayed by the geographic routers, which are in charge of moving a geographic message from a sender to the target area [62-63]. The geographic routers are essentially IP routers that are geographically aware; each

geographic router keeps track of the target area until it reaches the GAC which can do service for the target area. The central GAC has a geolocation table, which stores BS coordinates and GMMT coordinates (It will be described later), so the GAC knows which BS are involved in the geocast service. GAC will first send the information of target area boundary (with delay-sensitivity level) to the BSs involved in the geocast service. The BSs will broadcast the target area information (with delay-sensitivity level) to their own MTs. Normally, the MTs in GA CAHAN will act as the MTs in pure cellular networks, i.e., the GPS receiver is idle and is not activated. However, after receiving the target area information, the MT in GA CAHAN will start to activate its GPS receiver to receive GPS signal and find its own coordinates. The MT itself determines the geocast membership by mapping the target area boundary onto its own coordinates. The MT within the target area is called geocast member mobile terminal (GMMT).

- 1) If the delay-sensitivity level of geocast service is high, GMMT will not activate its ad hoc communication system and each BS will broadcast the geocast message to each GMMT directly. Only the GMMTs receives the geocast message (other MTs are idle). In this case, the GMMTs will not relay any messages and GA CAHAN will act as the traditional cellular networks.
- 2) If the delay-sensitivity level is medium, the GMMT will activate its ad hoc communication system and send coordinate update (CUP) packet with current coordinates to its own BS for searching the AHS Head. In this case, the geocast message will first be sent from BS to the AHS Heads, then each GMMT will broadcast the geocast message with its maximum transmitted power to its neighbor which didn't receive the geocast message. Since the geocast message is

relayed by the AHS Head, the total geocast energy in system will be reduced.

- 3) When the delay-sensitivity level is low, the GMMT not only sends CUP packet to its BS (after activating its ad hoc communication system) but also sends HELLO packet with current coordinates to its neighbors for searching its less-power next-hop MT (Section 4.3) to further reduce the total geocast energy in GA CAHAN.

To have reliable location information, the CUP packet will be sent via one-hop cellular radio link, not the multi-hop peer-to-peer radio link. The location information is only sent by the GMMT that needs to update its coordinates. If the updating coordinates is not needed, only a GMMT ID will be send to BS via CUP packet.

Unless we specify the delay-sensitivity level of geocast service, the remainder of this chapter about GA CAHAN will always assume that delay-sensitivity level of the geocast service is low, i.e., each GMMT will have to send CUP packet, activate its ad hoc communication system, and send HELLO packet.

When the delay sensitivity of geocast service is low, the ad hoc communication system of an MT is activated after it becomes a GMMT and the GMMT will periodically broadcast a short HELLO packet that includes its coordinates and ID to its neighborhood with fixed maximum transmitted power. Assuming the use of single precision floating-point numbers, it needs four bytes of the packet length to represent each latitude or longitude. A total of eight bytes are sufficient to address the whole surface of earth with precision down to 0.1 miles [62-63]. The geolocation update interval is defined as the time interval between coordinate-update HELLO packet arrivals. The length of the geolocation update interval depends on the MT mobility, the network density, and the ad hoc communication range. The optimization of the geolocation update interval is needed.

Once each GMMT within the AHS sends a HELLO packet, the subgraph corresponding to the AHS is constructed.

On the other hand, after receiving the CUP packets and getting the coordinate information of GMMTs, BS can traverse the planar graph G within its cell such that it will have a view on the topology of AHS subgraph within its cell. The traversal of the graph G can be done by using breadth-first search (BFS) algorithm. The function for searching the AHS Head is distributed into each BS. The BS assigns an AHS Head for each AHS based on the information it has. An algorithm for searching AHS Heads with less-power consideration will be given in Section 4.3. However, each individual BS only can find the AHS Heads for the AHSs within its own cell. Searching the AHS Heads for the AHSs on cellular boundary must be done by the GAC. If the distance from a GMMT to its neighbor BS is less than (or equal to) the summation of BS maximum communication range and maximum ad hoc communication range, the GMMT will be regarded as lying on the cellular boundary between its own BS and the neighbor BS. During traversing the planar graph G within its cell, BS will also check if any GMMT lies on the cellular boundary. Only the coordinate information of the AHS which has at least one GMMT on cellular boundary is forwarded to GAC so the coordinate-update overhead from BS to GAC will be less. After getting all the coordinate information of AHSs on cellular boundary, GAC will have a view on the topology of AHS subgraph on cellular boundary and the same algorithm for searching AHS Heads will also be processed. Moreover, when the size of the target area is increased and covers more cells, only the coordinate information of the GMMTs on the new cellular boundary is added into the geolocation table of the GAC, not all the GMMTs. The total memory occupation

of the geolocation table in GAC of GA CAHAN is small and only linear with the number of GMMTs N , i.e., the complexity of the geolocation table in GAC is only $O(N)$. Therefore, the GA CAHAN has good system scalability.

The data packets will be broadcasted from the BS to the AHS Heads and relay to the neighbor set N_{AHS} of the AHS Heads. The neighbor set N_{AHS} will forward the same data packets to their neighbors. The data packet will be received only once in each GMMT. The alternative to relaying information is using the less-power route. Using the less-power route will further reduce the total transmitted power in GA CAHAN. An algorithm for searching less-power route will be given in Section 4.3.

1) HELLO packet

HELLO (13 bytes) = {transmitter MT ID 2 bytes, broadcast ID 2 bytes, HELLO message type 1 byte, latitude 4 bytes, longitude 4 bytes}

transmitter MT ID 2 bytes	broadcast ID 2 bytes	HELLO message type 1 byte	latitude 4 bytes	longitude 4 bytes
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MT/BS ID format (2 bytes)

0	1	16 bits
MT 1	ID number 15 bits	
BS 0		

HELLO broadcast ID is 1111111111111111

2D geographic positioning <latitude, longitude>, ex. <40.48640, -74.44513>
 latitude: -90 degree (south) to 90 degree (north); longitude: -180 degree (west) to 180 degree (east)

2) CUP packet

CUP (13 or 14 bytes) = {transmitter MT ID 2 bytes, receiver BS ID 2 bytes, CUP message type 1 byte, latitude 4 bytes, longitude 4 bytes, ad hoc communication range 1 byte (it is needed only when the communication range is changed)}

transmitter MT ID 2 bytes	receiver BS ID 2 bytes	CUP message type 1 byte	latitude 4 bytes	longitude 4 bytes	ad hoc communication range 1 byte
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4.2.3 Maintenance of Geocast membership List and AHS Head List

During the geocast service, the MTs in GA CAHAN can be classed to be: 1) normal MTs: The normal MT is the MT which doesn't lie within the cells involved in geocast service (i.e., it didn't receive any target area information). 2) nonGMMTs: The nonGMMT is the MT which lies within the cells involved in geocast service, but it

doesn't lie within the target area. 3) GMMTs: The GMMT is the MT which lies within the target area. A normal MT will act as the MT in pure cellular networks (i.e., Both GPS receiver and ad hoc system are idle). A nonGMMT will only activate its GPS receiver. A GMMT will activate the GPS receiver and the ad hoc system. Due to the MT mobility, the topology of wireless networks is dynamic such that the status of the MT has to be confirmed and the geocast membership of a MT has to be updated. The maintenance of the geocast membership list is done by the "host" cellular system. When any new MT joins its cell, the BS involved in geocast service will dispatch the target area information to the new MT. The MT will start/continue to activate its GPS receiver to receive GPS signal, find its own coordinates, and determine the geocast membership until it leaves the BSs which are involved in the geocast service. That is to say, the procedure for activating GPS receiver, finding coordinates, and determining geocast membership will be periodically executed only when a MT lies in the cells which are involved in the geocast service. Once a MT leaves the cells involved in the geocast service, the MT in GACAHAN will rest its GPS receiver and back to a normal MT as it in pure cellular networks.

Once a nonGMMT, whose ad hoc system is not activated, has already crossed the boundary of the target area and entered into the target area, the nonGMMT will become a GMMT and it will start to send the coordinate information to BS. On the other hand, if a GMMT has already left the target area, it will automatically back to be a nonGMMT, rest its ad hoc system, and stop sending coordinate information to BS. In each update interval, the BS and GAC update the information of the instantaneous geocast membership list. If a MT enters or leaves the target area, the MT will start, continue, or rest its ad hoc

communication systems. From the new geocast membership list, the GAC/BS determines if it also needs to update the AHS Heads (Section 4.3.2). If any new AHS Head on cell boundary is ascertained or any GMMT on cell boundary is no longer the AHS Head due to the mutable topology of its AHS, the GAC has to deliver these updated AHS Head IDs to BSs. However, the GAC only needs to deliver the related portion of the updated messages to the BSs in their respective service areas.

4.2.4 Geocast Power Consumption Models

We assume that our system consists of an arbitrary number of services by considering that each MT is associated with a different quality of service (QoS) requirement. The maximum packet error rate (PER) in the QoS requirement can be mapped into an equivalent signal-to-interference ratio (SIR) requirement. The transmission quality E_b/I_0 should be greater or equal to the QoS requirement (i.e., the minimum SIR requirement), where E_b denotes bit energy and I_0 denotes total interference density.

1) *Ad hoc geocast power consumption model of GA CAHAN*: As mentioned before, in peer-to-peer model of GA CAHAN, we use a multirate CDMA protocol with request-to-send/clear-to-send bandwidth reservation mechanism as the medium access technique. The multirate CDMA protocol for the GA CAHAN peer-to-peer model can be found in [33]. Moreover, we assume that all packets are sent on a transmitter-based code. Each GMMT listens to the common channel (control channel), and the transmitter GMMT instructs the receiver GMMT on which channel (spreading code) to transmit its data by sending request-to-send (RTS) control packet through the common channel. Therefore, the GMMT can transmit the same geocast packets successfully to different receiver GMMTs at the same time. However, in a geocasting, it won't be possible for

every less-power next-hop MT (Section 4.3.1) to receiver the geocast signal at the same received power since the geocast signal might have to satisfy the SIR constraint at other GMMTs as well. Let \mathfrak{R} be the set of the less-power next-hop MTs where user $k \in \mathfrak{R}$ is required to maintain a SIR over its minimum SIR requirement. The geocast power $\bar{P}_{i,\mathfrak{R}}$ from GMMT i to its less-power next-hop MT set \mathfrak{R} is:

$$\bar{P}_{i,\mathfrak{R}} = \max_{k \in \mathfrak{R}} \left[\frac{\gamma_{i,k}^{ah} r_{i,k}^{ah} \left(\sum_{\{m,l\} \neq \{i,k\}} \bar{P}_{m,l} \alpha_{m,k} + \eta_0 \omega_{ah} \right)}{\alpha_{i,k} \omega_{ah}} \right] \quad (5.1)$$

where $\bar{P}_{m,l}$ denotes the transmitted power from MT m to MT l , $\gamma_{i,k}^{ah}$ denotes the minimum SIR requirement for $\{i, k\}$, $r_{i,k}^{ah}$ denotes the minimum requirement of data rate for $\{i, k\}$, $\alpha_{i,k}$ denotes the attenuation from MT i to MT k , ω_{ah} denotes available bandwidth in ad hoc communication system, and η_0 denotes the thermal noise spectral density.

2) *Cellular geocast power consumption model of GA CAHAN*: For the cellular network model of GA CAHAN, two distinct frequency bands between BS and AHS Heads are used separately to carry the information on the upstream and the downstream. The multirate CDMA is the medium access technique between the BS and the AHS Heads. The measure of transmission quality E_b/I_0 in the multirate CDMA cellular network model of GA CAHAN can be found in [46]. We assume that all packets are sent on a transmitter-based code. Each AHS Head listens to the common channel (control channel), and the BS instructs the AHS Head on which channel (spreading code) to transmit its data. Therefore, the BS can transmit the same geocast packets successfully to different AHS Heads at the same time. However, in a geocasting, it will not be possible

for every AHS Head to receiver the geocast signal from BS at the same received power since the geocast signal might have to satisfy the SIR constraint at other AHS Heads as well. Let \mathfrak{S} be the set of the AHS Heads where user $k \in \mathfrak{S}$ is required to maintain a SIR over its minimum SIR requirement. The *downlink* geocast power $P_{BS,\mathfrak{S}}$ from BS ν to its AHS Head set \mathfrak{S} is:

$$P_{BS,\mathfrak{S}} = \max_{k \in \mathfrak{S}} \left[\frac{\gamma_{BS,k}^c r_{BS,k}^c (\alpha_{BS,k} \sum_{j \in \mathfrak{S}, j \neq k} P_{BS,j} + I_{extBS,k} + \eta_0 \varpi_c)}{\alpha_{BS,k} \varpi_c} \right] \quad (5.2)$$

where $P_{BS,j}$ denotes the transmitted power from BS ν to MT j , $\gamma_{BS,k}^c$ denotes the minimum SIR requirement for MT k , $r_{BS,k}^c$ denotes the minimum requirement of data rate from BS to MT k , s denotes the set of MTs being served from the BS ν , $\alpha_{BS,k}$ denotes the attenuation from BS ν to MT k , $I_{extBS,k}$ denotes the total external interference from BSs other than BS ν (as experienced by the MT k), ϖ_c denotes available bandwidth in cellular system, and η_0 denotes the thermal noise spectral density.

4.2.5 Synchronization Issue

Since each MT in GA CAHAN has a low-power GPS receiver, the synchronization in GA CAHAN can be achieved by use of the absolute time information provided by GPS up to 100 ns resolution [32][51]. In a synchronous network, each MT wakes up regularly to “listen” for change and goes back to the sleep mode to conserve power. After wakeup, each MT may execute the protocol and starts data transmission on the optimal link or goes to the sleep mode. The implementation of the synchronization in GA CAHAN can have benefits below: 1) Saving MT power consumption: In an asynchronous BS system,

MT must wake up multiple times and for longer periods to monitor the different BSs. However, in a synchronous system, each node wakes up regularly to listen for change and goes back to the sleep mode to conserve power. 2) Fast cell search: The process of searching for a cell and synchronizing to its downlink scrambling code is often referred to as cell search. With synchronized BSs, all cells can use shifts of the same scrambling code, so that a cell is identified by a unique code phase shift of the scrambling code. But, in an asynchronous CDMA system, cell can only be identified by using distinct scrambling codes. Therefore, synchronization will help GA CAHAN to have fast cell search. 3) Fast completion of handoffs: no need to adjust the timing of each individual MT in soft handoff. The MT does not need to decode any signal from the new BS prior to handing off. 4) Other benefits such as increased reliability of common channels and more options for accurate location-based services.

4.3 Less Power Considerations in Geocasting

When the transmitter MT and the receiver MT have an unobstructed line-of-sight path between them, Friis free space equation shows that, given a fixed carrier frequency and the known received power of receiver MT, the transmitted power of transmitter MT depends on: 1) The transmission distance. 2) The transmitter antenna gain and the receiver antenna gain, which are all related to the physical size of the antenna (the effective aperture). 3) The communication system hardware losses, which can be filter losses, transmission line attenuation, and antenna losses [9]. We assume that there is no communication system hardware loss and each MT has the same transceiver hardware (i.e., the same physical size of the antenna). Then the transmitted power of transmitter

MT will have exponential relation only with transmission distance [9][68][32].

4.3.1 Less-Power Problem Formulation, Analysis, and Approach

A less-power route can be constructed. To find the less-power route, every GMMT v_i ($i = 0, 1, \dots, k-1$) in the path sequence $\langle v_0, v_1, v_2, \dots, v_k \rangle$ has to search the relay nodes between it and its neighbor GMMT v_{i+1} such that the total power consumption is minimized. Here, we assume that GMMT u , GMMT w , GMMT x , and GMMT k are the neighbors of GMMT "s" as shown in Figure 4.2. GMMT u is the farthest neighbor of "s"; GMMT w is an intermediate node between "s" and u . In geocast service, all of these neighbors are destination GMMTs and need to receive geocast messages. Let $d[x_1, x_2]$ denote the distance between GMMT x_1 and GMMT x_2 , $P[x_1, x_2]$ denote the transmitted power required from x_1 to x_2 , $route[x_1, x_2]$ denote the route from x_1 to x_2 , and C_i denote the fixed receiver power consumption of GMMT i to receive and store messages. The route from GMMT "s" to GMMT u is $route[s, u]$. However GMMT w is the neighbor of GMMT u and can receive the messages directly from GMMT "s". Therefore, it is possible to route the information from "s" to u through a relay GMMT w between the source and the destination, and be able to achieve smaller total transmit power than the total transmit power $P[s, u]$ used for $route[s, u]$. The new path is composed of $route[s, w]$ and $route[w, u]$, and the power consumption for the new path will be $P[s, w] + C_w + P[w, u] + C_u$.

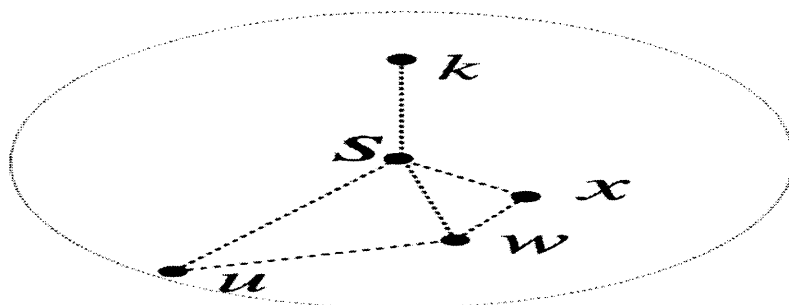


Figure 4.2 Ad hoc communication range of GMMT "s".

From the distance properties of relay nodes in [32], if GMMT w is a minimum-power relay node between GMMT " s " and GMMT u , the distance relation between GMMT s , GMMT w , and GMMT u must be

$$d[s,w] < d[s,u] \quad \text{and} \quad d[w,u] < d[s,u]. \quad (5.3)$$

Therefore, we can determine if GMMT w is a relay node by using this condition.

With the less-power consideration, GMMT w can be selected to be the relay node if the power consumption from GMMT " s " to GMMT u via GMMT w is less than the power consumption from GMMT " s " to GMMT u directly, i.e.,

$$P[s,w] + C_w + P[w,u] + C_u < P[s,u] + C_u. \quad (5.4)$$

Therefore, the power property for a single relay node w is

$$P[s,w] + C_w + P[w,u] < P[s,u]. \quad (5.5)$$

Furthermore, if GMMT x , which lies between GMMT " s " and GMMT w , is the relay node from GMMT " s " to GMMT w , the power property will be

$$P[s,x] + C_x + P[x,w] < P[s,w]. \quad (5.6)$$

Add " $C_w + P[w,u]$ " to the both sides of (5.6). From (5.5) & (5.6), we find the power property of two relay nodes is

$$\begin{aligned} & P[s,x] + C_x + P[x,w] + C_w + P[w,u] \\ & < P[s,w] + C_w + P[w,u] \\ & < P[s,u] \end{aligned} \quad (5.7)$$

i.e., the power consumption of the message traversing two relay nodes (GMMT x and GMMT w) is less than the power consumption of message traversing a single relay node (GMMT w). Generalizing the statement above, we can get Theorem 1.

Theorem 1- Less Power Property: In less-power consideration, suppose x_1, x_2, \dots, x_n are

relay nodes between the transmitter GMMT “s” and its neighbor GMMT u . Also, assume the node sequence x_{i-1}, x_i, x_{i+1} satisfies the distance relationship between two nodes and their relay given in (5.3). The route resulting in the less total transmitted power between GMMT “s” and its neighbor u is the node sequence $\langle s, x_1, x_2, \dots, x_n, u \rangle$.

Proof: The less power from GMMT “s” to its neighbor u

$$\begin{aligned}
 &= (P[s, x_1] + C_{x1} + P[x_1, x_2] + C_{x2} + P[x_2, x_3] + C_{x3} \dots + P[x_n, u]) \\
 &< (P[s, x_2] + C_{x2} + P[x_2, x_3] + C_{x3} \dots + P[x_n, u]) \\
 &< (P[s, x_3] + C_{x3} \dots + P[x_n, u]) \\
 &< \dots \\
 &< P[s, u]
 \end{aligned}$$

Definition 2- A Set of Less-Power Relay Nodes & Less-Power Next-Hop MT: A vertex set $LP_{relay} = \{x_1, x_2, \dots, x_n\}$ in Theorem 1 is said to be a set of less-power relay nodes between node “s” and its neighbor u . The first relay node in the set of less-power relay nodes LP_{relay} is referred to as the less-power next-hop MT ($LP_{next-hop}$) of GMMT “s” to GMMT u . In Figure 4.2, the less-power next-hop MT from GMMT “s” to GMMT u (or GMMT w) will be GMMT x ; the less-power next-hop MT from GMMT “s” to GMMT k will be still GMMT k since there is no closer neighbor between GMMT “s” and GMMT k .

In case of high delay tolerant data transmission for geocasting, AHS Head transmits the geocast messages to a set of its less-power next-hop MTs after receiving messages from BS; similarly, a GMMT transmits the geocast messages to a set of its less-power next-hop MTs that didn’t receive that messages. The network density is defined as the average number of GMMTs being served in a cell site. When the network density is

greater, the distance between GMMT "s" and its less-power next-hop MT will be shorter on average.

On the other hand, from a graph theoretic point of view, each BS is a vertex in an AHS subgraph that has only one link connecting the BS to the AHS Head. Therefore, a set of the less-power next-hop MTs of BS comprises the AHS Head that is the selected GMMT that has the shortest distance from BS in an AHS.

4.3.2 Geolocation-Aware Routing Algorithms

1) *Less-power routing in peer-to-peer communication:*

Algorithm 1- Less-Power next-Hop MT Search (LPHS): The way a less-power next-hop MT is constructed was outlined in Section 4.3.1. The algorithmic description of exactly how a set of less-power next-hop MTs are found is as follows. Let each small letters (s , u , w , and k) denote a single vertex, the capital letter denote a set of vertices, N_s denote a neighbor set of GMMT "s", $d[x_1, x_2]$ denote the distance between GMMT x_1 and GMMT x_2 , $LP_{relay}[s, u]$ denote the set of less-power relay nodes between GMMT "s" and neighbor u , and $LP_{next-hop}[s]$ denote a set of the less-power next-hop MTs of the GMMT "s". $LP_{next-hop}[s]$ is a subset of the neighbor set N_s , i.e., $LP_{next-hop}[s] \subset N_s$. The searching process of a set of less-power next-hop MTs consists of the steps in Figure 4.3. A flow diagram depicting the LPHS algorithm is presented in Figure 4.4. The algorithm will be repeated for all other neighbors of GMMT "s".

```

step 1.  $LP_{next-hop}[s] \leftarrow \phi$ 
      if  $N_s \neq \phi$ 
        then pick a neighbor GMMT  $u \in N_s$ 
           calculate  $d[s,u]$ 
            $h \leftarrow u$ 
           mark  $u$ 
        else stop // This GMMT "s" is an isolated GMMT
step 2. while (an intermediate node  $w$  that exists between node "s" and  $u$ , AND it is closer to  $u$ ) // While loop
      do calculate  $d[s,w]$  and  $d[w,u]$ 
      if  $d[s,w] < d[s,u]$  and  $d[w,u] < d[s,u]$ 
        then  $h \leftarrow w$ 
            $u \leftarrow w$ 
           mark  $w$ 
       $LP_{next-hop}[s] \leftarrow LP_{next-hop}[s] \cup \{h\}$ 
step 3. if any other unmarked neighbor
      then pick one unmarked neighbor GMMT  $k$ 
          $h \leftarrow k$ 
          $u \leftarrow k$ 
         mark  $k$ 
         go to step 2
      else stop
  
```

Figure 4.3 LPHS algorithm.

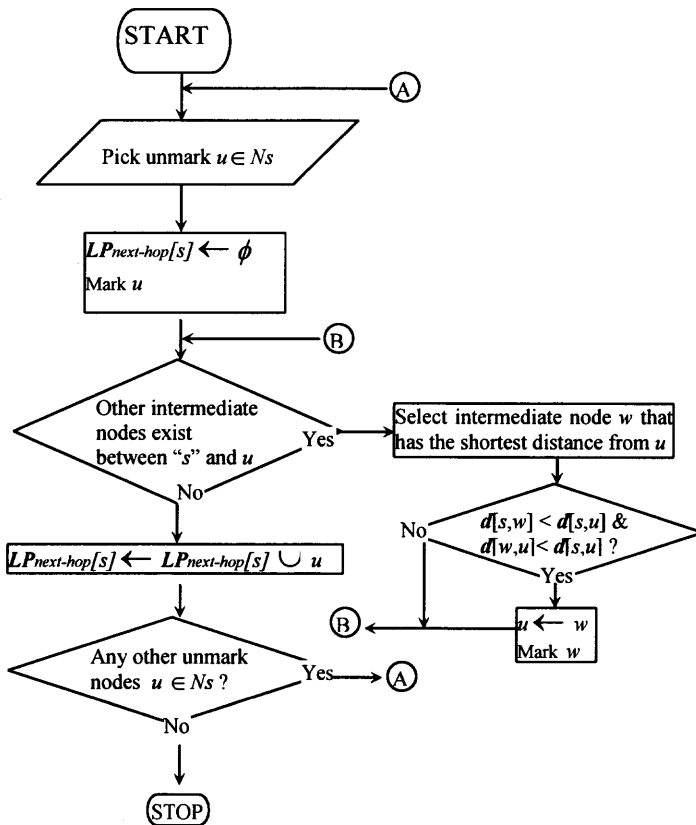


Figure 4.4 Flow diagram for LPHS algorithm.

2) *Less-power AHS Head search:*

Algorithm 2- AHS Head MT Search (AHMS): AHMS algorithm is a simple less-power AHS Head search algorithm. GAC/BS executes the AHMS algorithm after getting all the coordinate information of the GMMTs. The AHMS algorithm only considers how to ascertain an AHS Head in order to minimize the transmitted power of BS/MT. The basic concept was outlined in Section 4.3.1. A set of the less-power next-hop MTs of BS comprises the AHS Head that is the selected GMMT that has the shortest distance from BS in an AHS. AHMS algorithm further reduces the transmitted power of BS. The searching process of the less-power AHS Heads consists of the following steps.

A) *Finding the bidirectional-link neighbors of a GMMT:* The GAC/BS periodically receives the coordinate information of the GMMTs. A GMMT that lies within the ad-hoc communication range of another GMMT is referred to as its neighbor (Definition 1). Let d_{ij} denotes the distance from GMMT i to GMMT j ($j \neq i$) and R_i denotes the ad hoc communication range of GMMT i . The d_{ij} can be found from the coordinate information. The R_i information can be found from the CUP packet. If $d_{ij} \leq R_i$, the GMMT j will be the neighbor of the GMMT i . Otherwise, the GMMT j will be the nonneighbor of the GMMT i . However, due to different ad hoc communication range for each GMMT, the unidirectional link may exist in graph G . To have an undirected graph, we only select the bidirectional-link neighbors.

B) *Determining each connected AHS:* The undirected graph $G = (V, E)$ corresponding to the set of all GMMTs within a target area of the GA CAHAN will be constructed after finding the bidirectional-link neighbors of each GMMT,

where V is the vertex set of G and E is the edge set of G . The breadth-first search (BFS) algorithm can be used to determine each AHS in the planar graph G . The BFS algorithm is one of the simple algorithms for searching a graph [39]. The traversal of the whole graph G could be started at any vertex. BFS algorithm picks any vertex in an AHS and systematically explores the edges of graph G to discover the vertices until no other new GMMT can be discovered in the AHS. An undirected AHS is connected if every two vertices in the AHS are reachable from each other. The determined AHS is connected since the BFS algorithm discovers all the vertices in an AHS via the bidirectional link. After determining an AHS, BFS algorithm will pick another un-discovered vertex and continuously discovers the other GMMTs in different AHS. Therefore, traversing the whole planar graph G with BFS algorithm can determine each AHS and find which AHS a GMMT belongs to. The several AHS subgraphs may exist in the whole graph G , and each GMMT may belong to different AHS.

- C) *Selecting an AHS Head from an AHS*: During traversing the planar graph G to determine each AHS, the AHS Head in each individual AHS can be also found. In traversing an AHS, an AHS Head will be the GMMT that has minimum distance from BS in an AHS. Let $d_{i,BS}$ denote the current distance from MT i to its BS. The AHS-Head selection is done by comparing all the current distance $d_{i,BS}$ ($i \in \text{AHS set } X$) in a AHS X , and the AHS Head of the AHS X will be the MT that currently has the minimum $d_{i,BS}$ in the AHS X .

4.4 Performance Evaluation & Numerical Study

4.4.1 Simulation Model

The simulation model of GA CAHAN was implemented using OPNET. In the simulation, the initial coordinates of all MTs are generated from an i.i.d. uniform distribution. The network density is defined as the average number of MTs being served in a cell. Varying network densities were chosen in simulations for both GA CAHAN model and cellular network model. For each network density, we estimated the total transmitted energy in an update interval. The simulation has capability to simulate a network with hundreds of MTs at the same time. The minimum power allocation scheme is implemented in both cellular system and ad hoc system. We assume that there is no noise. Each MT has the same transceiver hardware and QoS requirement; in our simulations, transmission quality E_b/I_0 is taken to meet QoS requirement $\gamma'_{i,v}$ ($E_b/I_0 = \gamma'_{i,v} = 7 \text{ dB} \cong 5$). The ad hoc communication range of GMMT is 200m. In simulations, we assume that delay-sensitivity level of the geocast service was low and the geocast messages were transmitted continuously from the MSC to the GMMTs within target area, i.e., every GMMT is a destination MT that is receiving the same messages. Since the geocast message is only sent to the GMMTs that didn't receive that message, each GMMT receives the same geocast message only once.

We have assumed that our system supports three different geocast services: Service I, Service II, and Service III. Each service has different size of target area. The size of the target areas in Service I is 500m x 500m, which is the smallest size of target area in our simulations. In Service I, the same size of the target area is drawn onto three different districts, which cover different number of cells. Their simulation result for

average transmitted energy on these three different districts is shown in Figure 4.5.a. The size of target areas in Service II is 900m x 900m. In Service II, the same size of the target area also is drawn onto three different districts. Their simulation result for average transmitted energy on these three different districts is shown in Figure 4.5.b. Finally, the size of target areas in Service III is 1300m x 1200m, which is the largest size of target area in our simulations. Figure 4.5.c shows their simulation result for average transmitted energy on three different districts.

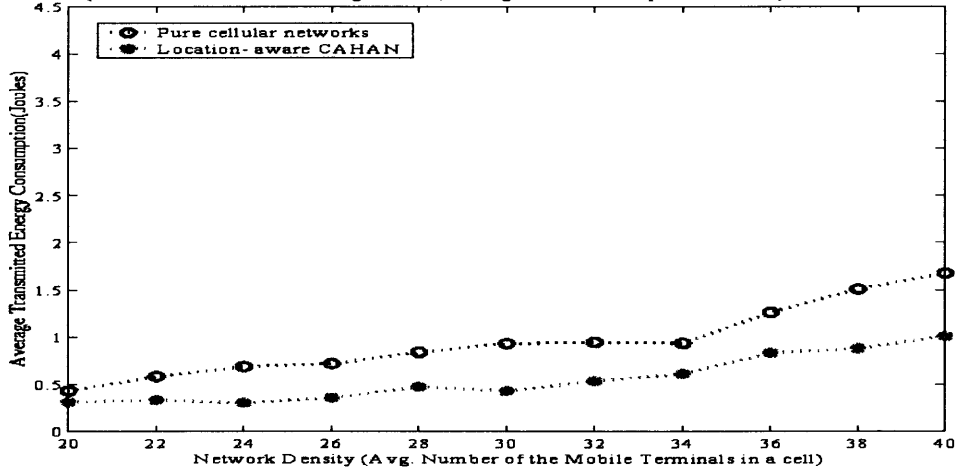
4.4.2 Simulation Results and Observations

The simulation results in Figure 4.5 show that GA CAHAN with LPHS/AHMS algorithm spends less total transmitted energy than pure cellular networks at every network density. The total transmitted energy will include the total energy for transmitting the data packets and control packets for BSs and GMMTs. As the size of target area is increased, in which more cells are likely involved, using GA CAHAN results in significant savings in total transmitted energy. The advantage of GA CAHAN is more evident when a target area is on a cell boundary and covers several cells. As mentioned before, when the target area covers several cells, all the BSs involved in the geocast service of the pure cellular network have to geocast the same messages to the target area using their maximum broadcast power. However, in the geocast service of GA CAHAN, the geocast message can be relayed by the GMMTs so GA CAHAN will need few BS to geocast the messages to the target area. If only one ad hoc subnet in the target area on cell boundary, GA CAHAN needs only one BS to geocast the messages such that GA CAHAN will decrease much total transmitted energy consumption for the geocast service. When the number of cells covered by the target area is increased, GA CAHAN can save larger transmitted

energy. On the other hand, the dense target area in GA CAHAN saves even more transmitted energy. As the network density is increased, the interference increases. The network capacity of CDMA system is interference limited. While the pure cellular network reaches its maximum network capacity, the GA CAHAN can still allow more MTs to enter the cells involved in geocast service.

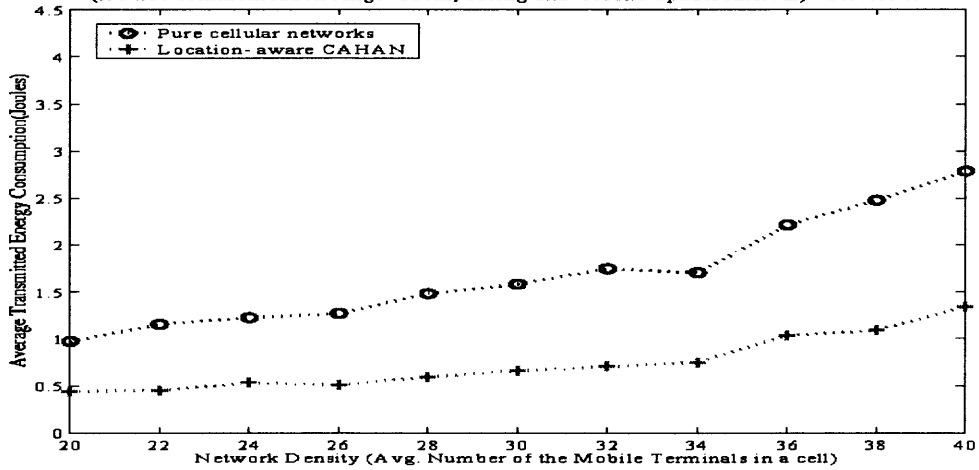
The simulation results in Figure 4.6 and Figure 4.7 show that energy consumption of HELLO and CUP packets in GA CAHAN. The energy consumption for HELLO and CUP packets is also counted in Figure 4.5. The energy consumption for HELLO and CUP packets in GA CAHAN is less. On the other hand, the GMMT in GA CAHAN also has to spend much less energy for forwarding data packets, since each GMMT forwards same message only “once” and only to its closer neighbors which didn’t receive the message. In a word, to save large transmitted energy of BSs, each GMMT just need to spend little energy for forwarding data packets and updating its coordinates.

Total Geocast Data Packet & Control Packet Energy Consumption of Cellular Networks vs. Location-Aware CAHAN (Ad hoc communication range: 200m, during one-second update interval) Service I.



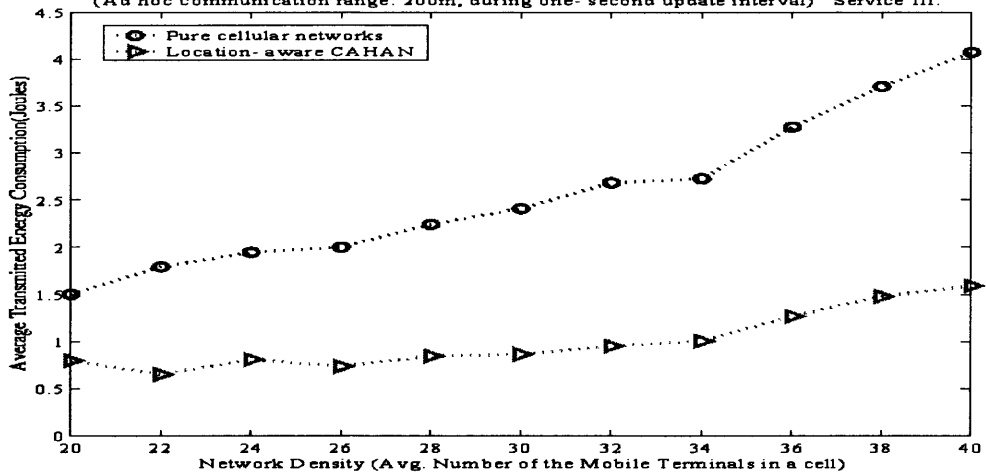
(a)

Total Geocast Data Packet & Control Packet Energy Consumption of Cellular Networks vs. Location-Aware CAHAN (Ad hoc communication range: 200m, during one-second update interval) Service II.



(b)

Total Geocast Data Packet & Control Packet Energy Consumption of Cellular Networks vs. Location-Aware CAHAN (Ad hoc communication range: 200m, during one-second update interval) Service III.



(c)

Figure 4.5 Average transmitted energy of GA CAHAN and pure cellular networks on the three different districts of service (a) Service I (the smallest target area) (b) Service II (c) Service III (the largest target area).

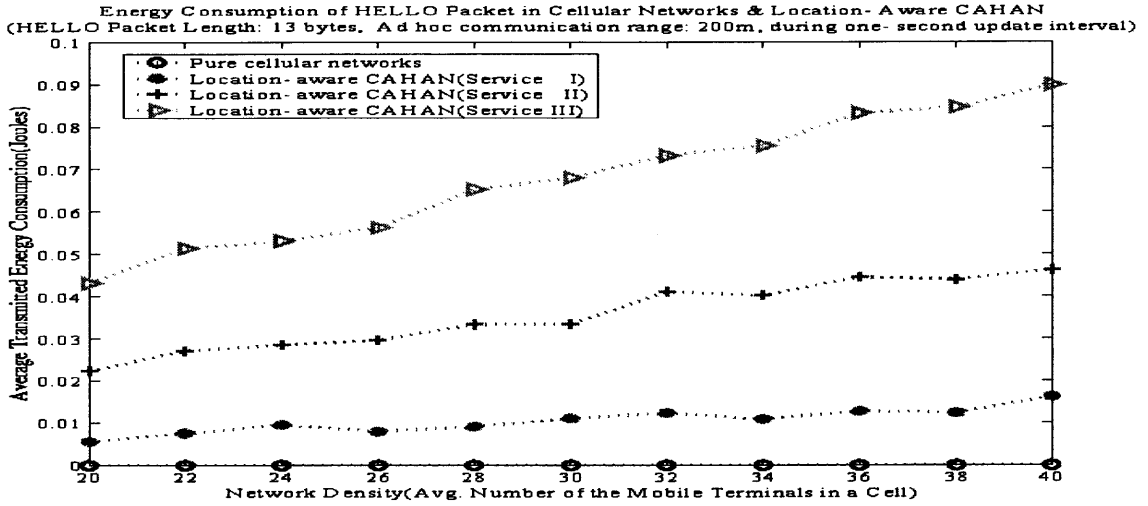


Figure 4.6 Energy consumption of HELLO packet in GA CAHAN and cellular networks.

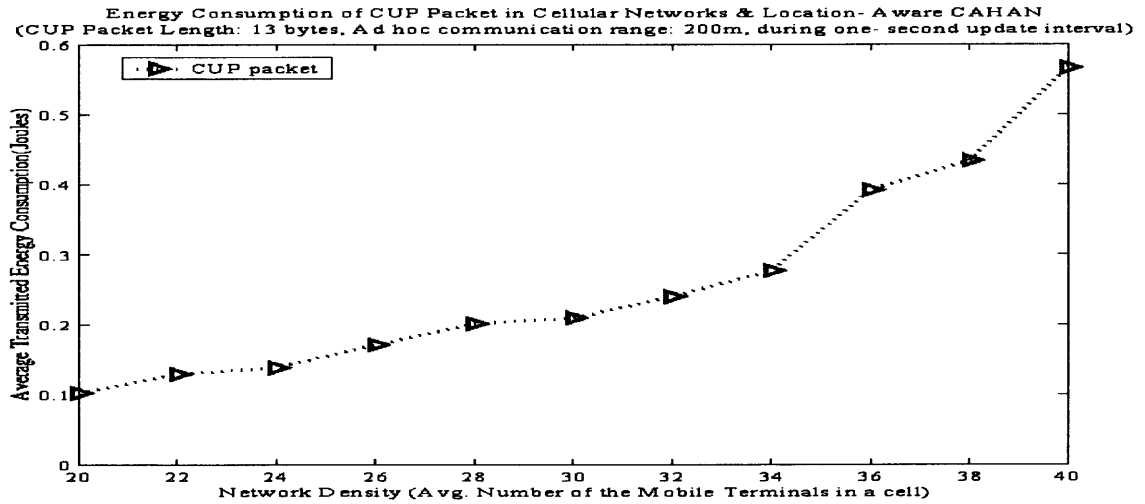


Figure 4.7 Energy consumption of CUP packet in GA CAHAN for the Services III which has the largest number of GMMTs (the worst case).

CHAPTER 5

CONCLUSION AND FUTURE WORK

The proposed CAHAN architectures benefit from existing relay MTs in the cellular network to achieve the optimal minimum transmitted power or the maximum network lifetime for wireless services without additional infrastructure. The proposed CAHAN has the next generation wireless system concept and has the ability to adapt to various QoS constraints for different wireless applications. The CAHAN can find the optimal minimum-power route or the maximum-network-lifetime route under bandwidth constraint, packet-delay constraint, or packet-error-rate constraint. The CAHAN also has good scalability and high reliability. The comparison of QCMP CAHAN and QCLE CAHAN shows that they have different advantages, i.e., *optimal* minimum power or maximum network lifetime under the QoS constraints. The advantage of CAHAN is more evident when there are many MTs lies on a cell boundary and some relay MTs are closer to BS. Especially, CHAN can find the optimal minimum-power route in the ad hoc subnet which lies on cellular boundary and covers several cells. That couldn't be done by the conventional multihop cellular networks. Moreover, the novel ASCP selection scheme dynamically selects suitable ASCPs such that the selection will balance all the MT battery energy and maximizes the network lifetime. Except CAHAN, no other previous works in the area of network-lifetime-extension schemes consider the QoS issue so far. The location awareness in GA CAHAN can be used to help not only geocast service but also resource management, mobility management, network optimization, and other location-based information services. The proposed CAHAN is a novel and practical

wireless networks.

5.1 Future Work

Currently, many new wireless applications are emerging, and there remain some important problems that require investigation. This section will describe the possible extensions of the current research for CAHAN. In the previous works, we propose the QoS constrained minimum power, network lifetime extension, and geocasting scheme for the wireless application in CAHAN. Here, we would like to extend the research scope by investigating other matters in CAHAN for our future work. The important topics, that need to be further studied, are described below.

5.1.1 Rational Cooperation in Cellular Ad Hoc Augmented Networks

In cooperative CAHAN, all the mobile terminals (MTs) belong to the same authority; they are motivated to cooperate in order to support the basic functions of the network. By cooperation, we mean that the MTs perform networking functions for the benefit of other MTs, i.e. intermediate MTs are expected to relay the packet for the destination MT. Therefore, lack of cooperation may have fatal effects on the network performance of the CAHAN.

However, the experience of cellular networks shows that as soon as the MTs are under the control of the end-users, there is a strong temptation to alter their behavior in one way or another. Moreover, with the progress of technology, it will soon be possible to deploy ad hoc networks for civilian application as well [67]. They could be "completely" self-organizing, meaning that the network would run solely by the operation of the end-users. In such networks, there is no good reason to assume that the MTs

cooperate, and the MTs tend to be "selfish" in order to save resources (battery power, memory, CPU processes ...). Each MT has its own authority and tried to maximize the benefits it gets from the network. We assume that each MT belongs to a different authority and stipulate a social contract such that the action of including more neighbors occurs only when MT has its own packet to send (or it can obtain something it wants), and MT may abandon neighbors to avoid to relay the packets from neighbors. For example, the user can tamper with the software/hardware of the MT and modify its behavior in order to save battery power. As the fraction of noncooperative MTs is increased, the network performance degrades dramatically, i.e., it will have high total transmitted power and interference. Finally, the performance of the CAHAN will back to the performance of pure cellular networks. Since MTs are self-interested and rational, there is no guarantee that they will follow a particular strategy unless we propose a reward policy or they are convinced that tampering our approach is not advantageous for the user. The reward policy could be that if a MT can forward more packets from other MT to its neighbor it will get more right to send its own packets to the destination via peer-to-peer transmission. However, there could be another better reward policy. Any new reward policy will be needed to be evaluated.

5.1.2 Power-Aware Multicasting in Cellular Ad Hoc Augmented Networks

For some wireless applications, it is necessary for one wireless device to send a message to all the other members in the same classified group. In the near future, group application will span many heterogeneous wireless networks accessible by wireless device. Delivering a message to such a group is called multicasting. Overcoming the changes of wireless multicast support will make possible a wide range of new group-

oriented mobile services. Multicasting is a kind of group communication that requires simultaneous transmission of messages from a source to a group of destinations. Multicasting is different than multiple unicast in which each packet will travel the same link only once in order to reach all members in a select group. Unlike broadcasting, multicasting involves sending a message to only a selected group of users. Multicasting in wireless needs router support such that only necessary multicast packets are duplicated, and no duplicate packet are sent through the same radio link.

If the multicast group in a cell of cellular network is small, the message in BS can be just duplicated and delivered separately to each individual member MT. This is a multiple-unicast scheme. But, if the group is large, this strategy is expensive due to wasting radio resource. Broadcasting could also be used to do the multicasting in cellular networks. In this case, each MT must process the multicast message and filter out messages from uninterested groups. This strategy will waste the CPU and battery power of nonmember MT, so it is inefficient scheme. Thus we need a new power-controlled MAC scheme to deliver a message to a well-defined group that is numerically large in size but small compared to the whole network. Power control scheme with multicast traffic in CAHAN will be investigated.

A linear multiuser detector can be used for multicasting application in CDMA ad hoc systems. Multiuser detectors are adopted to do session admission control for the multicasting problem [64]. We may use a multiuser detector at the MT receiver to mitigate the near-far problem in an ad hoc network. Setting up a multicast session involves three components: 1) Do session admission control. 2) Using multicast routing algorithm to form the multicast tree 3) Implementing a power control scheme to ensure

that signals for the existing sessions and the new session meet their SIR requirements. The SIR depends on the type of linear multiuser detectors being used such as - conventional (matched filter) detector, minimum mean-square error (MMSE) detector, and decorrelating detector [64]. The conventional detector matches the received signal to the spreading code of the signal interest. The MMSE detector is the optimal linear detector that maximizes the SIR. The decorrelating detector is optimal in the scenario when the interferer's powers tend to infinity. In conventional detector, the SIR at MT k for a signal from MT i is given by [64]

$$\gamma(i, k) = \frac{p_i}{\sigma_k^2 + \frac{1}{L} \sum_{(j=1, j \neq i)}^M p_j} \quad (5.1)$$

Where p_i is the power of the signal received from MT i at MT k , σ_k^2 is the noise power at MT k , L is a process gain, and M is the number of signals being processed by MT k .

The capacity is defined as the maximum number of signal that can be processes by the MT k while ensuring that the SIR is above the threshold γ_i for all signals. When users are power controlled so that all of them are received at a common value $p_{(k, \min)}$

each, the capacity \hat{C}_k at MT k is [64]

$$\hat{C}_k \leq \left[\frac{L}{\gamma_i} + 1 - \frac{L\sigma_k^2}{p_{(k, \min)}} \right] \quad (5.2)$$

The capacity results for multiuser detector can be adapted to do session admission control for multicasting problem. In a multicasting, it may not be possible for a MT to receiver all the signals that it processes at the same power since these signals might have to satisfy the SIR constraint at other MTs as well. Let Λ be the set of intended receivers.

Intended receiver $k \in \Lambda$ is required to maintain an SIR over γ_i . This requirement can be written as [64]

$$\gamma_i \leq \min_{k \in \Lambda} \left[\frac{\alpha_{jk} p_j}{\left(\frac{1}{L} \sum_{i \neq j} \alpha_{ik} p_i + \sigma_k^2 \right)} \right] \quad (5.3)$$

i.e.,

$$p_j \geq \max_{k \in \Lambda} \left[\frac{\gamma_i \left(\frac{1}{L} \sum_{i \neq j} \alpha_{ik} p_i + \sigma_k^2 \right)}{\alpha_{jk}} \right] \quad (5.4)$$

Where p_i is the power of the signal received from MT i at MT k , α_{jk} is the attenuation from MT j to MT k .

In the transmitter-based protocol (such as common-transmitter code), the primary collision cannot happen, and the broadcast will be inherently supported. In the transmitter-based protocol, all packets are sent on a transmitter-based spreading code, the transmitter MT i that has multiple transmitters can send packets successfully to different receiver MTs. The capacity performance of the minimum power allocation scheme can be improved by implementing multiple transmitters in MT. The data packets are sent on a transmitter-based code. If the multiple transmitters implemented in an MT, the MT can send data packet successfully to different receivers such that the throughput in system will be increased. As inactive node tune to the same spreading code, multicasting and broadcasting could be readily implemented.

To do multicasting in wireless networks, group management and a routing algorithm are required. The MT may join or leave a multicast group at any time. A

scheme to determine the group membership of an MT should be proposed. Multicasting can be achieved by explicitly joining interested users in a tree or mesh architecture. The tree-based approach prevents the occurrence of routing loops, but if one or more users leave the tree, it may break into two or more subtrees, complicating communications among group members. Mesh-based multicasting may have loops and thus consumes more resources, but user mobility has less impact on group connectivity.

The topology of wireless networks is very dynamic due to the MT mobility. Since the BS in CAHAN have direct connection with each MT, we can support minimum-power multicast tree for CAHAN by taking advantage of the quick update information of transmitted power cost. Moreover, maintaining the power-aware multicast tree in CAHAN will need less control packet overhead. The detailed implementation of the QoS constrained shortest-path multicast support in CAHAN will be further investigated. The research subject of the power-aware multicasting in CAHAN may include:

- Group management & group membership
- Power-aware multicast routing algorithm: shortest-path multicast tree & k shortest paths
- Power-control multicast scheme in CAHAN: Comparison of the power-control multicast scheme, multi-unicast scheme, and broadcast scheme on radio resource (allocated transmission rate and transmitted power)
- Hop-count and bandwidth constrained (multi-constrained)

APPENDIX A

CAHAN CDMA SYSTEM SPECIFICATION

- 1) Modulation: QPSK
- 2) Duplexing:
 - A) Cellular system: FDD
 - B) Ad hoc system: Bandwidth Reservation
- 3) Frequency range:
 - A) Cellular system
 - Uplink: 1850 - 1910 (or 824 - 849 MHz)
 - Downlink: 1930 - 1990 (or 869 - 894 MHz)
 - B) Ad hoc system
 - Peer-peer: 2010 - 2070 (or 914 - 939 MHz)
- 4) Channel bandwidth: 1.25MHz
- 5) Chip rate: 1.2288 Mcps
- 6) Power control rate: 800Hz
- 7) Maximum user data rate: 144kbps
- 8) Synchronized BS and MT
- 9) Transmitted power:
 - A) Max physical transmitted Power: 10W (in simulation)
 - B) Min physical transmitted power constraint: 10^{-13} mW (in simulation)

APPENDIX B

CDMA CAPACITY ENHANCEMENT TECHNIQUES

CDMA system is interference-limited. Some other techniques that may increase the link capacity [15]:

- 1) Diversity techniques: Multipath provides several replicas of the signal at the receiver. These replications can be used at the receiver by optimally separating and combining the total received power. Temporal diversity can be obtained through the use of error correcting codes in conjunction with time interleaving. Space diversity is obtained when spatially separated or differently polarized antennas are used. In multihop networks, a receiver can benefit from one other diversity domain that is obtained from receiving several replicas of the same packet in different time slots and transmitted or relayed from different nodes. It gives rise to diversity gain and coding gain.
- 2) Multiuser detection: Multiuser detection is a method to obtain the achievable capacity as the cochannel interference increases by receiving more packets from other users. It also has capability of reducing sensitivity of decoding to the near-far effect and power control. This results in a lower bit error rate in uplink and in high power conservation in downlink since varying transmit power may be used for near and far users. It has the potential to take advantage of the conserved power in multihop networking to increase capacity.
- 3) Multiple-in multiple-out radio links: Increase the number of channel between the transmitter and receiver by using more antenna elements at each site. The

increased capacity in multiple-in multiple-out radio links is due to two effects. First, by increasing the number of channels, mean capacity is increased almost linearly with the number of antenna elements. Second, by providing temporal, transmit, and receive diversity, channel reliability is highly improved for higher data rates.

- 4) Smart antenna: An M -element smart antenna can null $M-1$ interferers independent of the multipath environment. By adding routers to the cellular structure, as the number of MTs communicating to any MT is reduced, smart antenna can be more effective.
- 5) Interference cancellation: Interference cancellation is a linear filter and is used to reduce the interference.
- 6) Space-time coding: The space-time codes introduce temporal and spatial correlation into signal transmitted from different antennas, so as to provide diversity at the receiver and coding gain over an un-coded system.
- 7) Turbo codes: Turbo codes have relatively large coding gain with reasonable computation complexity. Turbo codes need less required SIR than convolutional codes for same PER.

APPENDIX C

LOCATION APPLICATIONS AND GPS TECHNOLOGY

Location service will play a major role for future wireless network services [17] [19], and, finding the location of the mobile terminal is one of the important features of the mobile communication system [2]. Many valuable location-based services can be enabled by this new feature. Wireless location using CDMA cellular networks bring with it the possibility of several applications that will benefit businesses as well as consumers. The potential location applications include [3]:

- Cellular system design and resource management
- Emergency assistance - emergency 911 (E-911)
- Network optimization: used to improve daily operations of a wireless network
- Location tracking: tracking package delivery, mobile commerce, wildlife tracking, etc.
- Fleet management, navigation, and intelligent transportation systems
- Location-sensitive billing: enabling price differentials based on the caller location
- Location-based information services: providing directions to find restaurants, hotels, cash machines, gas stations, etc.

Radio-based (terrestrial and satellite) technologies use BS, satellites, or other devices emitting radio signal to the mobile receiver to determine the position of the user. Commonly studied radiolocation techniques are signal strength positioning, angle of arrival (AOA) positioning, time of arrival (TOA) positioning, or time difference of arrival (TDOA) positioning [3]. The signal strength positioning uses a known mathematical

model describing the path loss attenuation with distance. The AOA system determines the mobile phone position based on triangulation. The intersection of two directional lines of bearing defines a unique position, each formed by a radial from a BS to mobile phone in a 2D space. The TOA system determines the mobile phone position based on the intersections of the distance circles. The propagation time of the radio wave is directly proportional to its traversed distance, and three measurements determine a unique position. The same principle is used by global positioning system (GPS), and the fourth measurement is required for a 3D solution. In TDOA system, the time difference is converted to a constant distance difference to two BSs to define a hyperbolic curve. The intersection of two hyperbolas determines the position. Another simple location method for mobile phone positioning is to use cell area (cell ID) of the caller as the approximate location of the mobile phone. The TOA method outperforms the AOA method by approximately 100 m in absolute position error when three BSs are used for location [3]. For high accuracy, location by means of measuring TOAs or TDOAs appear to be appropriate, whereas lower accuracy location can be obtained by other means such as signal strength positioning or by cell ID method.

However, the existing higher-accuracy TDOA-based methods may only achieve an accuracy of under 100 m in 67 percent of calls such that the TDOA-based methods alone may not meet the FCC requirements (50 m in 67 percent of calls). Moreover, the solution quality of TDOA/TOA/AOA depends heavily on the geometric location of the contributing BSs. On the other hand, the typical GPS receiver is accurate from 60 to 300 feet (18 to 91m) [4], therefore an obvious way to satisfy the FCC requirement is to incorporate GPS receivers into mobile phones [8]. GPS provides a means to determine

position, velocity, and time around the globe. The well-known differential GPS (DGPS) technology can improve the accuracy to three feet (0.9 m) or better. Offered free of charge and accessible worldwide, GPS is rapidly becoming a universal utility as the cost of integrating the technology into vehicles, machinery, computers, and cellular phone decreases. Increasing commercial use of the GPS will soon make it possible to locate anything, anywhere, and anytime. GPS consists of a network of 24 satellites in six different 12-hour orbital paths spaced. The satellites continually transmit military and civilian navigation data on two L-band frequencies.

But, there are some problems by combining GPS and mobile straightly for wireless applications [6-7]:

- GPS doesn't work in buildings or shadowed environments such as urban canyons.
- It is too slow for some services, particularly for emergency use.
- It is too costly and too bulky to be included in a modern mobile terminal.
- It drains common MT batteries at an unacceptably high rate.

The assisted-GPS (A-GPS) approach can overcome all the limitations above while providing better accuracy than any terrestrial-based approach or conventional stand-alone GPS at reasonable cost, even as complexity is reduced [6-8]. The A-GPS methods can satisfy the FCC requirements since its accuracy of under 20 m is a very reasonable expectation in 67 percent of calls [2]. The A-GPS technique can also employ DGPS methods in its location estimates to improve the accuracy to three feet (0.9 m) or better [6-7]. Therefore, A-GPS typically has the best positional accuracy, as compared with other geolocation system in location service.

The basic idea of A-GPS is to establish a GPS reference network (refer to as the

server) whose receivers have clear views of the sky and that can operate continuously. The MT GPS receiver (sensor) picks up the signal from the GPS satellites. At the same time, the server monitors the same satellite signals through its reference GPS receiver. This server is also connected with cellular infrastructure, continuously monitors the real-time constellation status, and provides data such as approximate handset position, clock correction, Doppler, etc. The server can perform the location computation taking advantage of additional information (terrain and network data) not generally available to a MT. The server has its own GPS receiver and, therefore, already knows with great accuracy what signals the MT GPS receiver is receiving. Through its connection with MSC, the A-GPS server knows the cell and sector where the mobile is located. Then, the A-GPS server will exchange information with the MT, essentially asking it to make specific measurements and collecting the results of those measurements. The basic idea behind A-GPS is to reduce the workload on the MT's GPS receiver as much as possible, at the expense of the A-GPS server. To this end, all complex calculations are done by the A-GPS server.

The availability of assisting GPS data provided by the server still allows the detection of the GPS signal at signal levels that are much lower than required by a conventional stand-alone GPS system. At the request of the mobile phone or location-based application, the assist data derived from the server are transmitted to the MT GPS receiver to aid fast startup and increase MT GPS receiver sensitivity. Acquisition time is reduced due to the fact that the search space has been predicted by the A-GPS server. This allows for rapid search speed and a much narrower signal search bandwidth, which enhances sensitivity and reduces mobile receiver power consumption. The MT A-GPS

receiver will take only a fraction of a second to make the measurements and relay them to the server. The A-GPS have the advantages [6-7]: 1) Inexpensive: A-GPS terminals are expected to incorporate geolocation functions at the chip level which therefore might be made for only a few dollars per handset more than conventional terminals. The network-side equipment promises to be much less costly than alternative approaches. 2) Applicable to all air interface. 3) DGPS level of accuracy. 4) Locations available in buildings and other heavily-faded situations. 5) Little or no new hardware needed in BSs, and no new connections between network elements. 6) Rapid acquisition time.

Third-generation mobile radio systems known as IMT-2000 (international mobile telecommunications for year 2000 and beyond) are currently one of the key communication technologies in reach, development, and international standardization bodies. The international consensus building and harmonization activities between different regions and bodies are currently ongoing. As wireless telecommunications move toward third-generation (3G) wireless, the global wireless industry has created two new partnership projects: 1) 3rd generation partnership project (3GPP), which has been concentrating on wideband code division multiple access (W-CDMA) and global system for mobile communications (GSM) systems. 2) 3rd generation partnership project 2 (3GPP2), which has been focusing on cdma2000 and cdmaOne systems. In [2], the article describes the location technologies specified by the 3GPP and the 3GPP2:

1) Location technologies specified by 3GPP:

A) Universal terrestrial radio access network (UTRAN): UTRAN is one of the most important members of the IMT2000 family and based on the W-CDMA

technique. Three location techniques have been specified for UTRAN: A-GPS, cell-ID-based, and observed TDOA (OTDOA) methods.

B) GSM EDGE radio access network (GERAN): In GERAN, three location methods are specified: A-GPS, cell-ID-based, and enhanced observed time difference (E-OTD).

2) Location technologies specified by 3GPP2: A-GPS and advanced forward link trilateration (A-FLT) have been standardized by Telecommunication Industry Association's TR-45.5 as IS-801. The next release, IS-801-A, is being handled by 3GPP2. Unlike GSM and W-CDMA, cdmaOne and cdma2000 are time-synchronized systems. Therefore, time difference measurement from them is easier than for GSM and W-CDMA. The basic idea of the A-FLT method is to measure the time difference between CDMA pilot signal pairs. Each pair consists of the serving cell pilot and a neighboring pilot. The time difference is converted to distance information.

From the description above, it shows that A-GPS location technology has been standardized by all the 3G systems. A-GPS doesn't require modifications of all BSs. The A-GPS server may be part of the mobile switching center (MSC). The received GPS signal needs only minimal processing in the MT before being retransmitted to the server over the wireless link. The main advantage of A-GPS lies in its superior performance. Other location techniques are typically characterized by comparatively poor accuracy and limited availability that makes them unsuitable for advanced location-based services[6-7].

For the emergency-assistance location service, the U.S. Federal Communication Commission (FCC) has made E911 a mandatory requirement for wireless

communications services [2]. In 1999, the FCC decided to tighten the Phase II location accuracy requirement from 125 m in 67 percent of all cases to 50 m in 67 percent of calls for hand-set-based solutions. In 2000, the FCC required wireless communications operators to offer operational location-capable phones. Moreover, the executive body of the European Union (EU), the European Commission (EC), has similar initiatives for their wireless emergency calls (E112). Coordination groups within EC have been organizing meeting to specify similar requirements as their counterpart in the U.S. A GPS technique typically has better accuracy that could satisfy the FCC E911 requirements, as compared with other single radio-based location technology. The other radio-based technologies alone such as TDOA, TOA, or AOA mayn't meet the FCC requirements (50 m in 67 percent of calls). The solution quality of TDOA/TOA/AOA depends heavily on the geometric location of the contributing BSs.

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