ABSTRACT

CROSS-LAYER DESIGN FOR WIRELESS SENSOR RELAY NETWORKS

by
Lichuan Liu

In recent years, the idea of wireless sensor networks has gathered a great deal of attention. A distributed wireless sensor network may have hundreds of small sensor nodes. Each individual sensor contains both processing and communication elements and is designed in some degree to monitor the environmental events specified by the end user of the network. Information about the environment is gathered by sensors and delivered to a remote collector.

This research conducts an investigation with respect to the energy efficiency and the cross-layer design in wireless sensor networks. Motivated by the multipath utilization and transmit diversity capability of space-time block codes (STBC), a new energy efficient cooperative routing algorithm using the STBC is proposed. Furthermore, the steady state performance of the network is analyzed via a Markov chain model. The proposed approach in this dissertation can significantly reduce the energy consumption and improve the power efficiency.

This work also studies the application of differential STBC for wireless multi-hop sensor networks over fading channels. Using differential STBC, multiple sensors are selected acting as parallel relay nodes to receive and relay collected data. The proposed technique offers low complexity, since it does not need to track or estimate the time-varying channel coefficients. Analysis and simulation results show that the new approach can improve the system performance.

This dissertation models the cooperative relay method for sensor networks using a Markov chain and an M/G/1 queuing system. The analytical and simulation results indicate system improvements in terms of throughput and end-to-end delay. Moreover, the impact of network resource constraints on the performance of multi-hop sensor networks

with cooperative relay is also investigated. The system performance under assumptions of infinite buffer or finite buffer sizes is studied, the go through delay and the packet drop probability are improved compared to traditional single relay method.

Moreover, a packet collision model for crucial nodes in wireless sensor networks is introduced. Using such a model, a space and network diversity combining (SNDC) method is designed to separate the collision at the collector. The network performance in terms of throughput, delay, energy consumption and efficiency are analyzed and evaluated.

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by
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CROSS-LAYER DESIGN FOR WIRELESS SENSOR RELAY NETWORKS

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To Zhigang, my parents and my family.

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CHAPTER 1

INTRODUCTION

With the development of the information society, the task for monitoring and sensing the physical world is becoming more complicated and diversified. The task changes over from sensing single parameter to multiple parameters, from a point to an interested area, from one sensor to a set of sensors. Meanwhile, the advances in wireless communications and electronics have enabled the development of small low-cost, low-power, multi-functional sensor nodes. These tiny nodes consist of sensing, data processing and communicating components. Networking these small sensors for a large sensing task leverages the concept of sensor networks. Sensor networks represent a significant improvement over traditional sensors and have many potential applications, such as system and space monitoring [1], target detection and tracking [2] [3], location sensing, and biomedical applications [4] [5].

A sensor network is composed of a large number of sensor nodes that are deployed either inside or very close to an interested area. The position of sensor nodes need not to be engineered or predetermined. This allows random deployment in inaccessible terrains or disaster relief operations. On the other hand, this also means that sensor network protocols and algorithms must possess self-organizing capabilities. Another unique feature of sensor networks is the cooperative effort of sensor nodes. Sensor nodes are fitted with onboard processors. Instead of sending the raw data to the remote receiver or collector directly, they use their processing abilities to locally carry out simple computations and transmit only required and partially processed data.

1.1 Protocol Stack for Sensor Networks

To reduce the design complexity, most networks are organized as a series of *layers* or *levels*, each one built upon the one below it [6]. The number of layers, the contents of each layer, and the function of each layer differ from network to network. However, the purpose of each layer is to provide certain services to the higher layers. The rules and conventions used in layer n are collectively known as the layer n protocol. A list of protocols used by a certain system, one protocol per layer, is called a protocol stack. The protocol stack of a sensor network consists of the physical layer, data link layer, network layer, transmission layer and application layer, as shown in Figure 1.1 . The physical layer is in charge of modulation, transmission and receiving techniques. As in many other shared-medium networks, the medium access control (MAC) protocol is able to minimize collision with the neighbor nodes. The data link layer is responsible for error control, data framing and multiplexing of data stream. The network layer addresses the needs of routing the data. The transport layer takes care of data flow maintenance. There are different applications depending on the sensing task in the application layer.

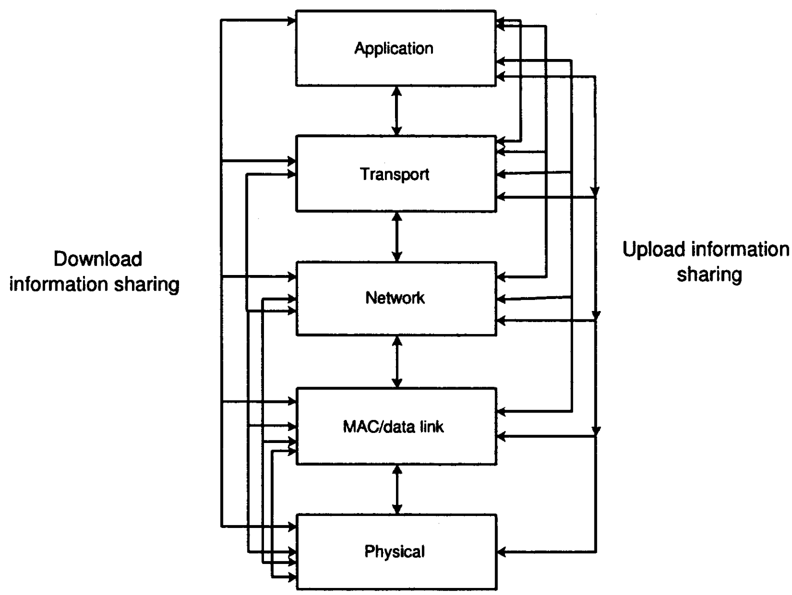

Figure 1.1 The sensor networks protocol stack and cross layer design

1.2 Architecture

According to the communication mechanism for collecting the sensing data, there are different type of architectures of sensor networks, as shown in Figure 1.2. The simplest one is direct connected, where each sensor directly sends information to the remote receiver/collector independent of each other [7]. It is energy-inefficient and impossible in many cases due to the large number of sensor nodes and limited transmission range.

The second approach is multi-hop routing. Because of the battery capacity limitation of sensor nodes, multi-hop but short range transmission usually consumes less average power than one-hop long distance transmission for a given pair of source and destination.

The third approach is cluster-based multi-hop, where sensors form clusters with neighboring sensors. One sensor will be elected as the cluster head according to some rules. Collected information will be transmitted to the cluster head first, then relayed to the remote receiver/collector. This approach localizes the traffic and can be scalable. It may reduce the overall data transmission when local data fusion and classification techniques are used. The disadvantage of this approach is that the energy consumption at cluster heads is much more than other approaches.

1.3 Design Challenges and Motivation

The general research challenges for real-time communication and coordination in sensor networks arise primarily due to the large number of constraints, many of them are new, that must be simultaneously satisfied. For example, large distributed computer systems (the Internet) have existed for a long time. However, solutions for communication and coordination in those systems did not have to address small capacities in memory, limited CPU execution speeds, and scarce communication bandwidth. Further, many classical solutions did not address minimization power, interacting with real world events through sensors and actuators. Some distributed embedded systems such as those that exist on submarines or in factories do deal with sensors and actuators, real-time constraints, cost,

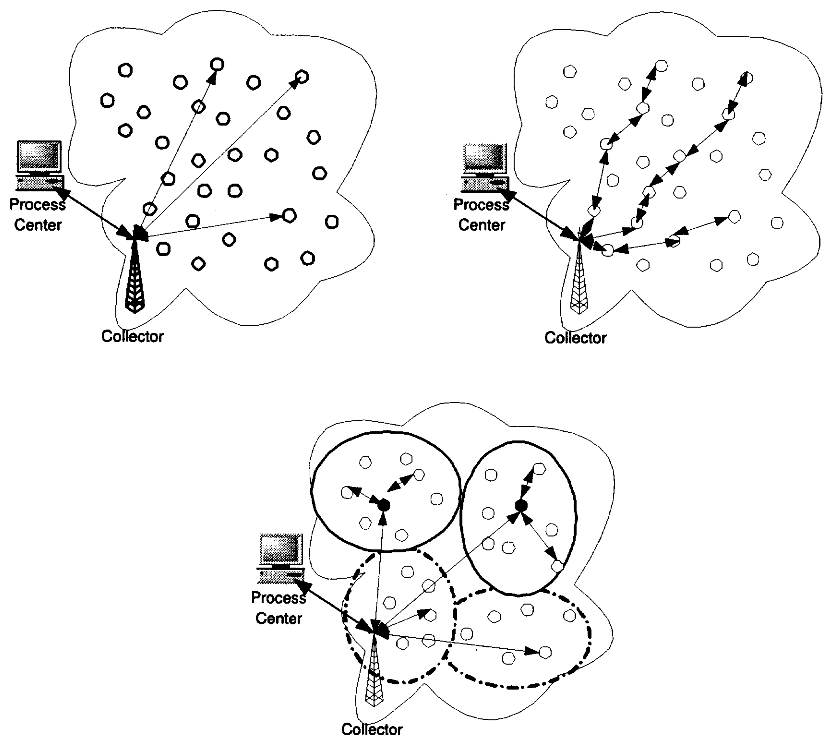

Figure 1.2 The three types of architecture of sensor networks.

and other issues, but they do not have solutions for many of the key issues such as those dealing with wireless communication, large scale, power management and unreliable devices. [8]

Unlike traditional wired or wireless networks, sensor networks poss certain characteristics with warrant their treatment as a special class of ad-hoc network.

Data-centric: sensor networks are largely data-centric, with the objective of delivering time sensitive data, in a timely fashion, to the required destination.

Application-oriented: While traditional wired and wireless networks are expected to cater to a variety of user applications, a sensor network is usually deployed to perform specific tasks. This property makes it possible to enable nodes to respond in an application-aware fashion. Data can be collected, appropriately aggregated with consideration of the requirement of the applications, and then acted on locally and/or forwarded to a higher level controller node (rather than simple end-to end data transfer).

Wireless sensor networks will have different challenges and design constrains than exiting wireless networks (such as: cellular networks and wireless LANs).

- **Resource constraints**

  The main resources in short supply are: power, CPU execution speed, memory, cost and communication bandwidth. For example, sensor networks run on small batteries and often need to operate for a long time, power conservation is a key issue in sensor networks. Because applications involving wireless sensor networks require long system lifetime and fault tolerance, energy usage must be carefully monitored. Furthermore, since the networks can be deployed in inaccessible or hostile environments, replacing the batteries that power the individual nodes is undesirable, if not impossible. Recent studies have shown that radio communication is the dominant consumer of energy in sensor networks [9]. Reducing energy consumption to extend lifetime is a primary concern in wireless sensor networks. Thus, protocol and algorithm should be designed with saving energy in mind. Moreover, not only these specific problems should be solved, but also the tradeoff is need to be considered.

- **Unpredictability**

  The sensor network is deployed in an uncontrollable environment; the wireless communication channel is subject to noise, interference and multipath fading; a single node is not reliable; the connectivity is time varying; old nodes may die or be removed from the network and new nodes may join in.

- **Large-scale**

  Since the number of sensors will be large, node densities will be high and large amount of data will be produced. Thus, large scale management techniques will be needed. This large scale network with large amount of nodes which deployed in a wide area faces many uncertainties and noise, so such a system must be self operating, self maintaining and self stabilizing.

- **Paradigm shift**

  Unlike traditional wireless cellular or Ad hoc networks, a single node is not important any more in a sensor network, and the collector or the end user is interested in the area/location based data content. For example, a user may want to know how many people in a particular room of a building or he may want to know that what room has people more than a certain number; he cares about the data themselves instead of which sensor responds the request.

- **Real time**

  A sensor network is used to monitor or sense the real world, it may has real time requirement. For example, when the temperature reach a dangerous level, it should be sensed and report to the controller in a short time.

1.4 Related Work

Due to recent advances in integrated circuit and MEMS technology, the small, low power sensing devices will be ready to be deployed in sensor networks in the near future.

Network protocols for wireless sensor networks, such as directed diffusion [10] and LEACH [11] [7], are also proposed. In directed diffusion, routes are dynamically formed as data are sensed. Initially, routes called gradients that link sources to sink are formed. Through data aggregation techniques, catching, and reinforcement message, the appropriate link is dynamically selected from the candidates. Links are created only when data of interest are sensed. Therefore, less energy will be used by using this protocol. LEACH is a protocol that uses hierarchy to reduce the data collected by sensors before sending it on to a central base station. Reducing the data that needs to be sent helps make LEACH more energy efficient.

Although research about energy efficiency for wireless sensor network is relatively new, many energy-efficient network protocols for ad hoc networks have been presented. In [12] [13], techniques to evaluate and design energy efficient routing and MAC protocols for wireless networks are presented. Energy efficient protocols that adapt transmit output power and/or error correction control parameters have been explored extensively by a number of researchers. In [14], the author designed an adaptive radio for wireless multimedia communications over ATM. Frame length and forward error correction parameters are adapted to lower energy consumption and improve throughput as conditions of the channel change. A similar study is performed by [15] in context of a cellular-style network, but the output transmit power is also considered. In [16], an energy-efficient protocol that just both RF transmit power and error control strategy is examined for 802.11 wireless LANs.

Cross-layer optimization has recently gathered a lot of attention in wireless communication [17]. It is a new definition of the overall design strategies for wireless communication system, and it breaks the classical open systems interconnection (OSI) model [18]. Traditionally each layer has ignored the other layers and this consideration can simplify protocol design and treatment, however it is suboptimal for wireless communication systems. In wireless communication systems, multiple users intend to get access the medium and transmit their information, and such medium inherently vary in both the time and frequency domain. Although a variety of different layer schemes have been designed for wireless systems in order to efficiently mange the scarce radio resources and provide certain QoS requirements to mobile users, the performance of such systems can be optimized by considering some vertical coupling between layers. Among all the possible combinations of layers involved in this interlayer interaction, the inherent variability of the physical layer in wireless system makes this the most suitable layer for participating in such kind of mechanisms. Indeed, systems components such as medium access control (MAC) protocols, radio link control mechanism, radio resource management schemes, and routing algorithms can benefit from some degree of awareness of the time and frequency varying characteristics of the radio channel. System performance could arise from some communications between different layers, considering certain smart interactions between them in the system design [19] [20] [21].

1.5 Contribution and Outline of the Dissertation

The dissertation emphasizes on the energy efficient cross-layer design and multiple diversity combination in wireless sensor networks. At first, the issue of developing an energy-efficient cooperative routing protocol using space time block codes (STBCs) of a multi-hop sensor network is considered [22]. The modelling of steady state of the system is established. Then the network performance and the energy efficiency are analyzed.

In Chapter 3, since the overhead of the packets is also an important energy waste source and the channel estimating based on the pilot which is a kind of overhead is complex, the non-coherent communication and STBC should be considered. The differential STBC method is developed in Chapter 3 in order to combat the multipath fading and the radio interference [23]. The proposed method can reduce the calculation complexity for channel estimation and reduce the overhead at the same time.

Furthermore, a skip free negative process and an M/G/1 queueing system are used to model the system from the source to the destination [24]. The network performance, such as throughput and delay are analyzed. The more practical situation is considered, and the constraints of the network resources on the performance the network are studied, the drop probability and go through delay are also discussed [25].

In Chapter 5, this resaerch introduce the concept of crucial nodes in wireless sensor networks, and then the definition of the network lifetime is given [26]. In order to extending the lifetime of the crucial nodes as well as the whole network lifetime, a space and network diversity combining (SNDC) methods is presented to separate the packets collision [27] which is the major source of energy waste in wireless network. The network performance, such as throughput and delay, is analyzed and evaluated. The average energy consumption of the crucial nodes is also investigated.

Finally Chapter 6 concludes the dissertation, and present current and future research work.

CHAPTER 2

SPACE-TIME BLOCK CODING FOR COOPERATIVE RELAYS IN WIRELESS SENSOR NETWORKS

2.1 Motivation

In wireless sensor networks, radio interference and multipath fading make wireless transmission unreliable [28]. Using diversity is an effective approach to combating multipath fading, it is also able to enhance transmission power efficiency. In cooperative diversity, several nodes form a kind of coalition to assist each other with packet transmission [29]. The nodes jointly act like a multi-antenna transmitting array, and the destinations act like a multi-antenna receiving array through interchange of messages.

The STBC is an effective solution to enhance transmission power efficiency and reduce the effect of multipath fading. The challenge for implementing the STBC at a single node is that multiple transmitting and/or receiving antennas are required. Although the low-cost and small size sensor nodes can not satisfy such a requirement, suitably chosen cooperative nodes can provide transmission diversity. The *user cooperative diversity* utilizing distributed antennas belonging to multiple users, creates a "virtual array" by sharing their resources. The *amplify-and-forward* [30] and *decode-and forward* [31] algorithms for information relay have been developed. In this chapter, a new scheme is proposed for multi-hop sensor networks, where each data packet is transmitted by the chosen multiple sensors simultaneously, and at the sink, the received data is combined with the data stored and forwarded from the chosen neighbor node, the Transmitting/Receiving (Tx/Rx) space diversity is built up. In contrast, only one sensor is selected to perform transmission or relay per hop per routing path in traditional schemes. The new scheme utilizes two transmitting and two receiving sensors with the Alamouti STBC [32] to achieve the full rate full diversity measure.

2.2 Link Quality Based Cooperative Data Dissemination

Consider a multi-hop wireless sensor network, shown in Figure 2.1. Where a sink node sends queries and collects sensing information from sensors [33]. Usually, a sensing event is initiated by a sink or injected to a sink by a human operator. Such event is also called *interest*. A *interest* is directed to the sink's neighbors via broadcasting and eventually reaches an appropriate node whose function is to perform this query. During the broadcast stage, each node also knows the link quality of one hop toward the node initiating the interest. Upon receiving the query, a sensor replies to the *interest* by sending the sensing data backward to the sink.

To utilize multipath diversity for the data transmission between a sensor and a sink, the sensor will select two links with best quality. For next hop, the two nodes will respectively select a distinct link with best quality. For the two nodes who are only one hop away from the sink, they select an additional node (doorway node) [34] who is also one hop neighbor of the sink. The purpose of a doorway node is to get additional copies of transmitted packets. It caches the packets and send them to the sink during the final transmission period. Therefore, the sink has multiple copies of original sensing data. Due to the multipath diversity, the average transmission power at each node, then, is expected to be reduced significantly while achieving the same bit error rate. This power efficient feature is critical to sensor networks.

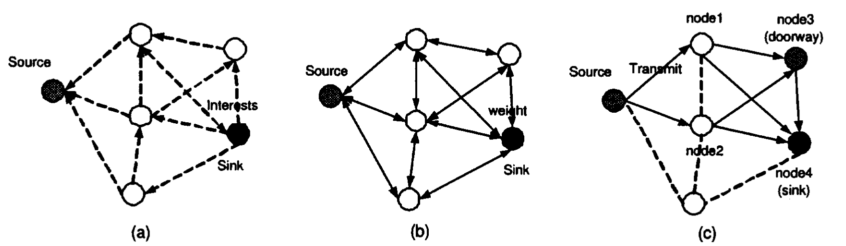

Figure 2.1 New transmission and diversity combining scheme for wireless sensor networks a) Interest propagation (b) Link quality setup (c) Data delivery along cooperative path

2.3 Cooperative Diversity with STBC

Consider a wireless sensor network with multiple sensors, where a sensor (source) wants to transmit packets to the destination via cooperative routing. In the first hop, multiple nodes receive the packets from the source sensor. In the conventional single transmission scheme, only one of these nodes is chosen to relay the packets to the second hop. In the proposed scheme, 2 nodes with the best link quality are chosen to relay the message with STBC code [35], as shown in Tab. 2.1.

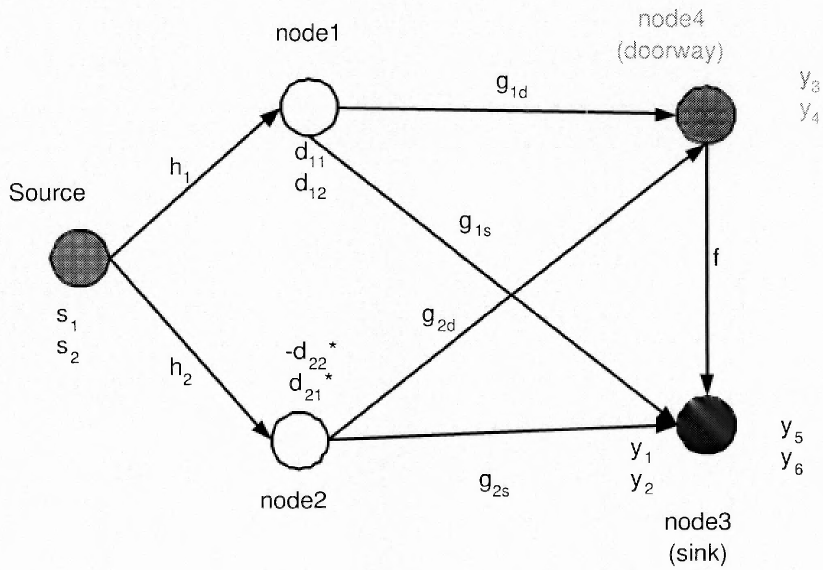

Figure 2.2 Transmission and diversity combining scheme

The source sends two consecutive data, $\mathbf{s} = \begin{bmatrix} s_1 & s_2 \end{bmatrix}^T$. The ith relay node receives corrupted versions of s, i. e.

$$\mathbf{d}_i = \begin{bmatrix} d_{i1} \\ d_{i2} \end{bmatrix} = h_i\mathbf{s} + \mathbf{w}_i, \quad i = 1,\ 2. \tag{2.1}$$

where h_i is the normalized channel coefficient between the source and the ith relay node, $h_i \sim CN(0, 1)$, and the noise vector $\mathbf{w}_i = \begin{bmatrix} w_{i1} & w_{i2} \end{bmatrix}^T \sim CN(\mathbf{0}, \sigma_w^2\mathbf{I})$.

The two relay nodes (node 1 and node 2) re-order and forward the received data according to the Alamouti code.

$$\mathbf{X} = \begin{bmatrix} \mathbf{x}_1 & \mathbf{x}_2 \end{bmatrix} = \begin{bmatrix} d_{11} & -d_{22}^* \\ d_{12} & d_{21}^* \end{bmatrix}$$

The received data at the sink (node 3) is,

$$\mathbf{y}_{node3} = \sum_{i=1}^{2} g_{i,s}\mathbf{x}_i + \mathbf{v}_{node3}$$

where $g_{i,s} \sim CN(0,1)$ is the fading factor between ith relay node and the sink, and $\mathbf{v}_{node3} \sim CN(\mathbf{0}, \sigma_v^2\mathbf{I})$ is the noise vector.

Rearranging data in $\mathbf{y}_{node3}$, I have

$$\begin{bmatrix} y_1 \\ y_2^* \end{bmatrix} = \underbrace{\begin{bmatrix} g_{1,s}h_1 & -g_{2,s}h_2^* \\ g_{2,s}^*h_2 & g_{1,s}^*h_1^* \end{bmatrix}}_{\mathbf{H}_{node3}} \begin{bmatrix} s_1 \\ s_2^* \end{bmatrix} + \underbrace{\begin{bmatrix} g_{1,s}w_{11} - g_{2,s}w_{22}^* \\ g_{1,s}^*w_{12} + g_{2,s}^*w_{21}^* \end{bmatrix} + \begin{bmatrix} v_1 \\ v_2^* \end{bmatrix}}_{\mathbf{n}_{node3}}. \quad (2.2)$$

Table 2.1 Transmission and Relay Scheme

time	transmit node1	transmit node2	receive node4 (doorway)	receive node3 (sink)
t_1	d_{11}	$-d_{22}^*$	y_3	y_1
$t_1 + T$	d_{12}	d_{21}^*	y_4	y_2
		node4		node3
t_2		y_3		y_5
$t_2 + T$		y_4^*		y_6

Note that the coefficient matrix $\mathbf{H}_{node3}$ is unitary, and the noise term $\mathbf{n}_{node3}$ is white with variance $||\mathbf{g}||^2\sigma_w^2+\sigma_v^2$. The received packet can be decoded and detected using standard ML method. The received packet is stored and will be combined with relay packet from doorway node. Similarly, the received signal in the doorway node (node 4) is

$$\mathbf{y}_{node4} = \sum_{i=1}^{2} g_{i,d}\mathbf{x}_i + \mathbf{v}_{node4}$$

where $g_{i,d} \sim CN(0,1)$ is the fading factor between the ith relay node and the doorway node, $\mathbf{v}_{node4} \sim CN(\mathbf{0}, \sigma_v^2\mathbf{I})$ is the noise vector. Re-arranging $\mathbf{y}_{node4}$ has the form

$$\begin{bmatrix} y_3 \\ y_4^* \end{bmatrix} = \underbrace{\begin{bmatrix} g_{1,d}h_1 & -g_{2,d}h_2^* \\ g_{2,d}^*h_2 & g_{1,d}^*h_1^* \end{bmatrix}}_{\mathbf{H}_{node4}} \begin{bmatrix} s_1 \\ s_2^* \end{bmatrix} + \underbrace{\begin{bmatrix} g_{1,d}w_{11} - g_{2,d}w_{22}^* \\ g_{1,d}^*w_{12} + g_{2,d}^*w_{21}^* \end{bmatrix} + \begin{bmatrix} v_3 \\ v_4^* \end{bmatrix}}_{\mathbf{n}_{node4}}. \tag{2.3}$$

The doorway node then forwards the data in (2.3) to the sink,

$$\begin{bmatrix} y_5 \\ y_6 \end{bmatrix} = f \begin{bmatrix} y_3 \\ y_4^* \end{bmatrix} + \begin{bmatrix} n_5 \\ n_6 \end{bmatrix} \tag{2.4}$$

where f is the channel coefficient between the doorway node and the sink. Combining (2.2), (2.3) and (2.4), leads to the standard formulation of the Alamouti STBC with 2 transmitting and 2 receiving antennas. That is,

$$\underbrace{\begin{bmatrix} y_1 \\ y_2^* \\ y_5 \\ y_6 \end{bmatrix}}_{\mathbf{y}} = \underbrace{\begin{bmatrix} \mathbf{H}_{node4} \\ f\mathbf{H}_{node3} \end{bmatrix}}_{\mathbf{H}} \begin{bmatrix} s_1 \\ s_2^* \end{bmatrix} + \mathbf{n} \tag{2.5}$$

Due to the unitarity of $\mathbf{H}_{node3}$ and $\mathbf{H}_{node4}$, the traditional STBC combining algorithm with multiple receiving antennas can be used [36] to decode the information at the destination.

$$\begin{bmatrix} \hat{s}_1 \\ \hat{s}_2^* \end{bmatrix} = \mathbf{H}^H \mathbf{y}. \tag{2.6}$$

The combination of the transmission, relay, receiving and decoding from the source to the sink appears to higher layers as a virtual bit pipe with a bit error rate (P_e). The role of P_e in the expression of throughput and delay will be shown later.

2.4 Energy Consumption and Protocol Efficiency

Assume that nodes communicate over a slow fading channel with additive white Gaussian noise. Consider that one node transmits data to another over such a channel. The energy per bit over noise at the receiver is [2]

$$\frac{E_b}{N_0} = \frac{P_t}{P_{loss}\alpha} \cdot \frac{1}{W N_{th} N_{rx}} \tag{2.7}$$

where P_t is the transmission power, P_{loss} is the large scale path loss, α is the average attenuation factor due to fading, W is the signal bandwidth, N_{th} is the thermal noise and N_{rx} is the noise at the receiver known as the noise figure. In general, $P_{loss} \propto \frac{1}{4\pi d^k}$, $2 \leq k \leq 4$.

The transmit power P_t can be written as

$$P_t = P_{loss}\alpha W N_{th} N_{rx} \frac{E_b}{N_0} \tag{2.8}$$

Assume N nodes are selected to transmit the data packet to the sink. The average energy consumption per bit is

$$E = E[E_i] = \frac{1}{N} \sum_{i=1}^{N} P_{ti} T_i$$

where E_i is the energy required at node i to transmit data, and

$$E_i = P_{ti} \cdot T_i$$

where $P_t(i)$ is the transmission power and T_i is the duration of the data transmission.

In order to achieve an optimal operating point with respect to energy consumption of a wireless sensor network, the RF transmission power and MAC retransmission should be trade-off. If there is no bit errors, no collision and no protocol overhead occur in a system, the energy E_{ideal} required to transmit data is

$$E_{ideal} = \bar{P}_t \times \bar{T} \tag{2.9}$$

where $\bar{P}_t$ is the mean transmitted power and $\bar{T}$ is the average transmission time.

The energy to transmit data is higher in reality because of protocol overhead and retransmission (bit error and collision). Therefore, define the protocol efficiency η_{pe} as the number of successful transmitted data bits B_{suss} over the number of overall transmitted bits B_{all}

$$\eta_{pe} = \frac{B_{suss}}{B_{all}}$$

where B_{all} includes MAC layer control packets, successful and retransmitted data bits and MAC + PHY packet header and trailer. η_{pe} indicates the protocol efficiency during the data transmission.

2.5 Simulation Results

2.5.1 Error Performance Simulation

It is assumed that the amplitudes of fading from each transmitting antenna to receiving antenna are mutually uncorrelated Rayleigh distribution and that the average signal power at each receiving antenna is the same. Future, assume that the receiver has perfect knowledge of the channel. Figure 2.4 shows the probability of the packet successful transmission of uncoded coherent BPSK for conventional method (no diversity) and space-time schemes (transmitting diversity only and tranmitting/receiving diversity) in Rayleigh fading. The performance of the new scheme is better than the conventional scheme and the transmission diversity methods. The diversity gain of the new scheme at BER of 10^{-3} is about 7 dB better than transmitting diversity only scheme and 18 dB better than the traditional method.

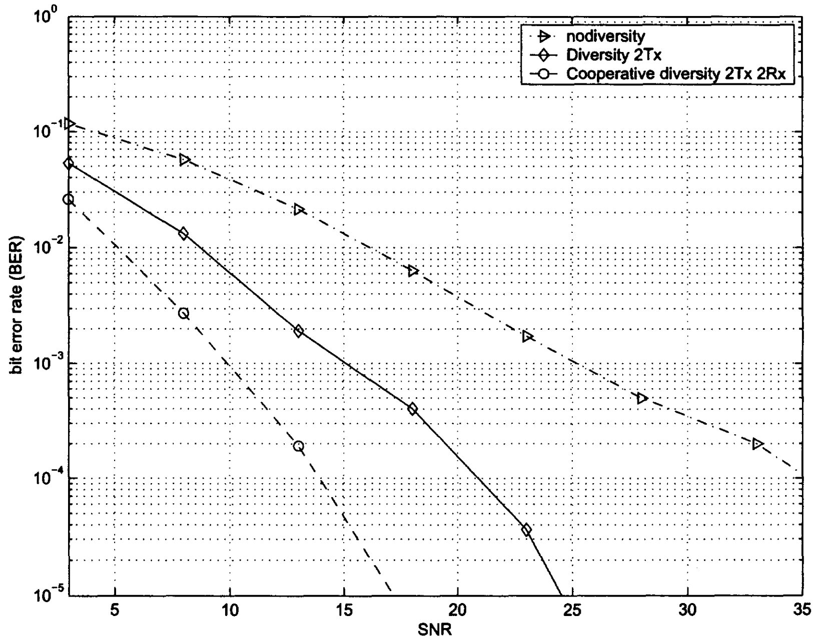

Figure 2.3 BER performance comparison of BPSK in Rayleigh fading

2.5.2 Throughput and Delay Simulation

Consider that the buffer size is infinite and then finite K, the packet arrival is a Poisson process.

Figure 2.5 Figure 2.6 shows the throughput versus traffic load for different approaches. The cooperative diversity approach with 2 transmitting cooperative nodes and 2 receiving cooperative nodes has the best performance. The delay performance is shown in Figure 2.7 and Figure 2.8 as a function of the traffic load. The simulation results

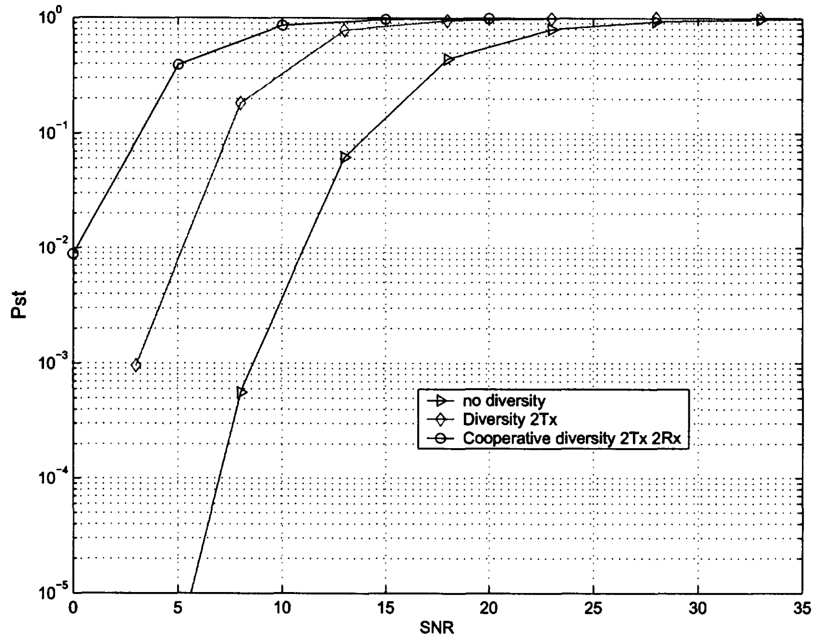

Figure 2.4 Probability of packet successfully transmission vs. SNR

demonstrate that the new scheme is better than transmitting diversity only approach and the single relay method.

2.5.3 Energy Efficiency Simulation

Assume the $P_{loss}\alpha$ is about 70 dB, the signal bandwidth is $W = 1$Mhz, $R = 1$Mbit/s, $N_{th} = -174$dBm and $N_{rx} \approx 10$dB, Figure 5.10 shows the simulation result for BER vs. transmitting power. It is important to note, the higher the transmission power, the lower the BER for the same method. To achieve the same BER, the new scheme needs the lowest transmission power. Figure 5.11 shows the average energy vs. BER. The new scheme can provide the best energy efficiency.

Figure 2.18 shows the protocol efficiency dependence on the transmission power used. The graph shows, that the protocol efficiency is very small for a relatively low transmission power for each transmission scheme. The primary reason are corrupted packets, which have to be retransmitted by the MAC protocol. By increasing the

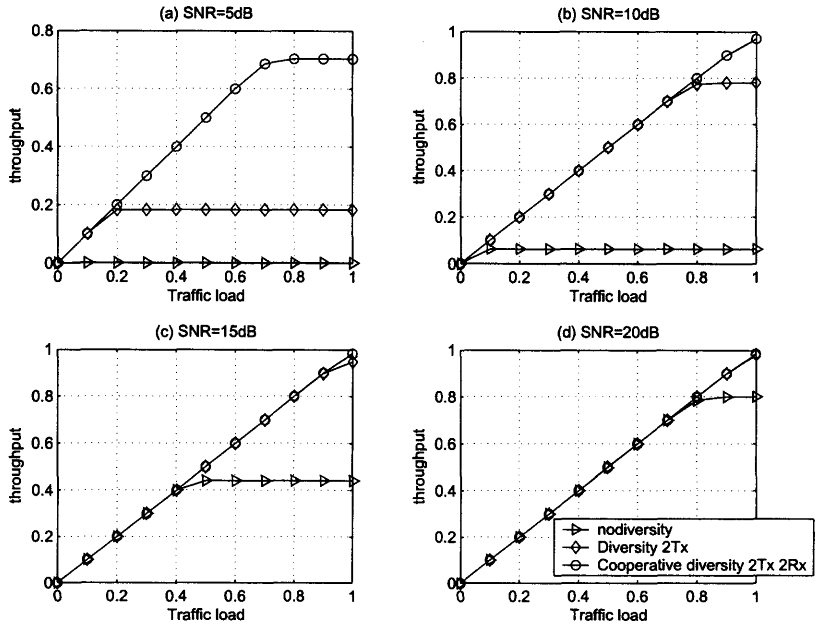

Figure 2.5 Throughput performance vs. traffic load comparison of BPSK in Rayleigh fading

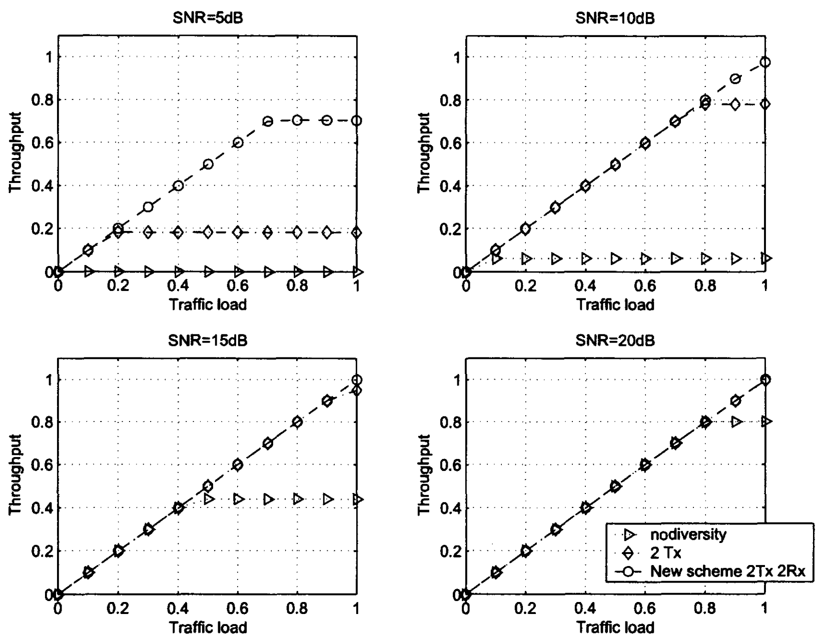

Figure 2.6 Throughput performance vs. traffic load comparison of BPSK in Rayleigh fading, analytical results

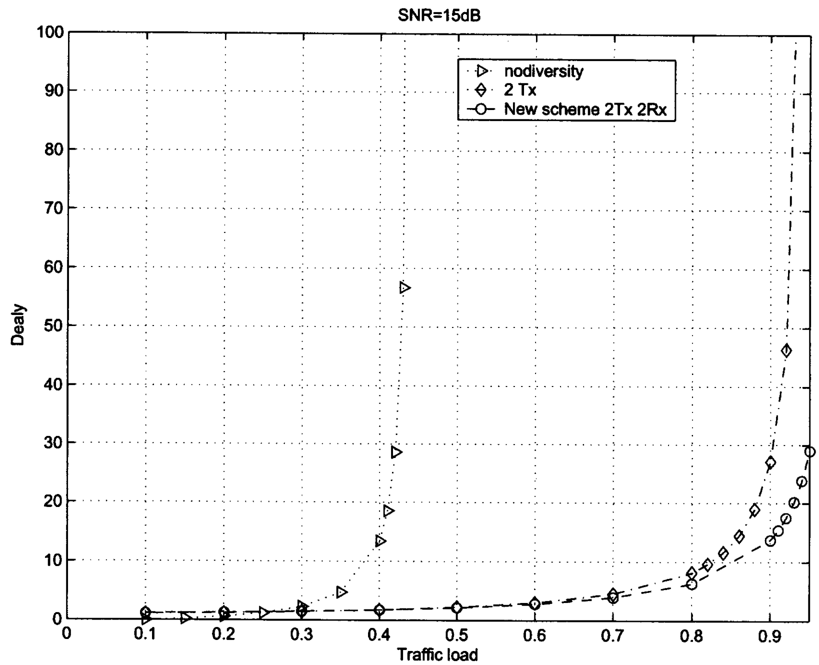

Figure 2.7 Delay performance vs. traffic load comparison of BPSK in Rayleigh fading (SNR=15dB)

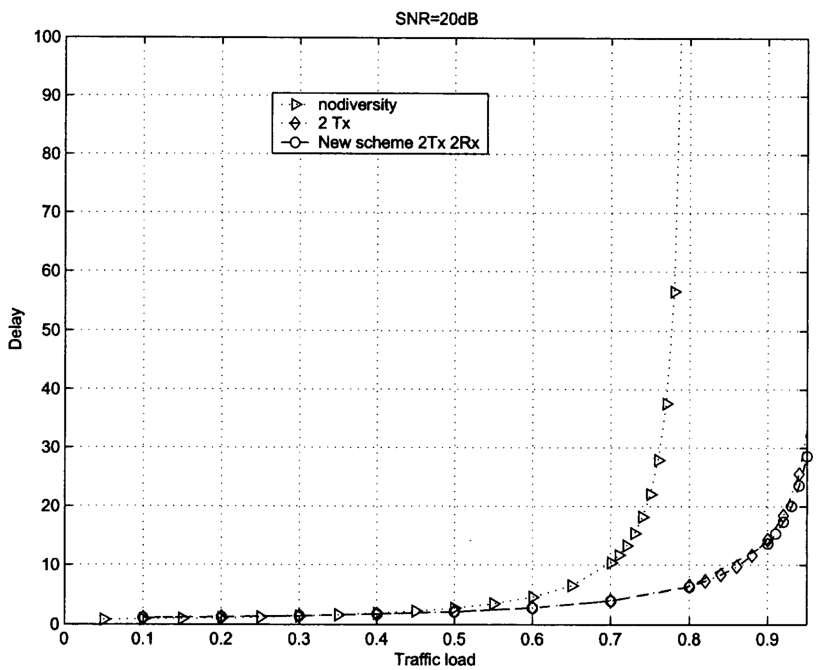

Figure 2.8 Delay performance vs. traffic load comparison of BPSK in Rayleigh fading (SNR=25dB)

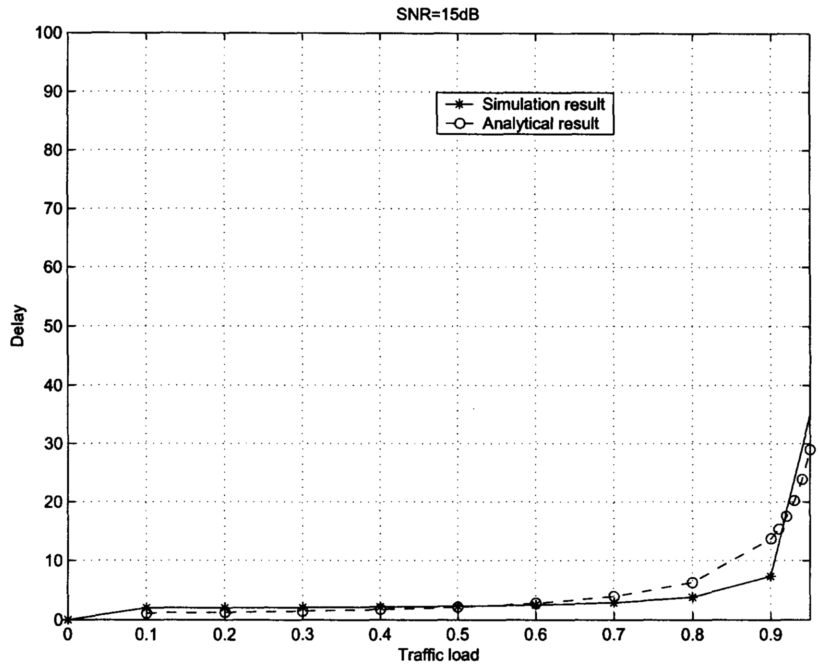

Figure 2.9 Delay performance (analytical and simulation Results) in Rayleigh fading(SNR=15dB)

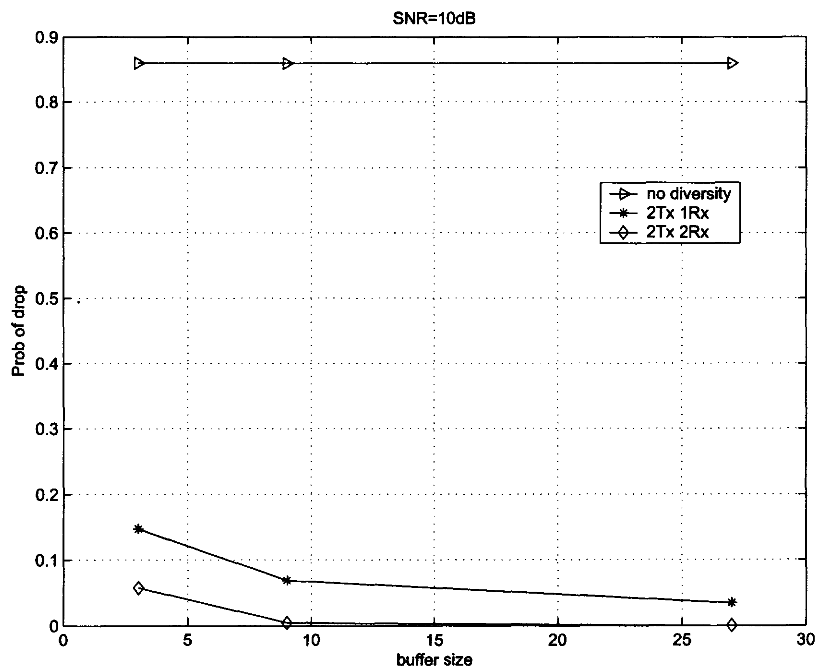

Figure 2.10 Drop probability vs. buffer size, analytical results (SNR=10dB, $\alpha = 0.5$, $\mu_{no} < \mu_{stbc} < 0 < \mu_{2t2r}$)

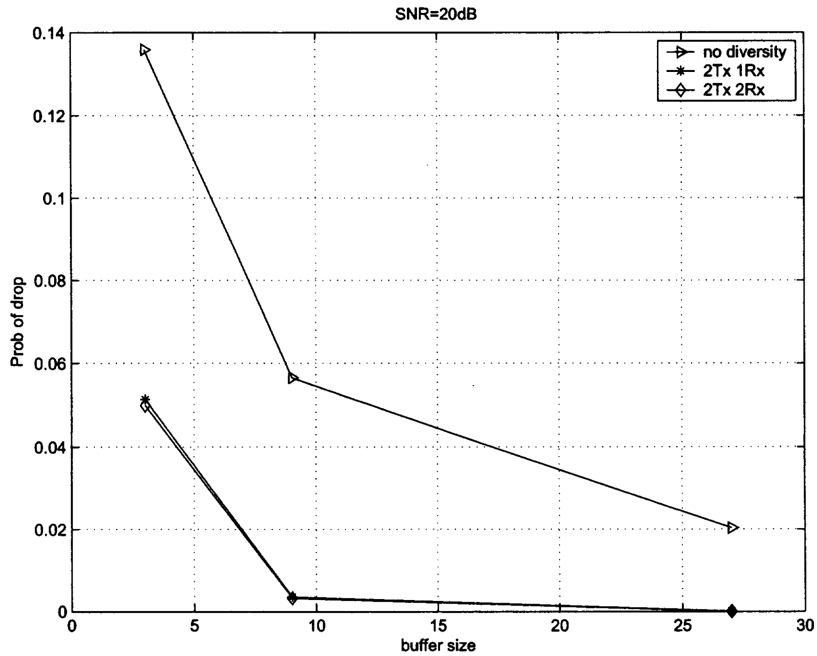

Figure 2.11 Drop probability vs. buffer size, analytical results (SNR=20dB, $\alpha = 0.8$, $\mu_{no} < 0 < \mu_{stbc} < \mu_{2t2r}$)

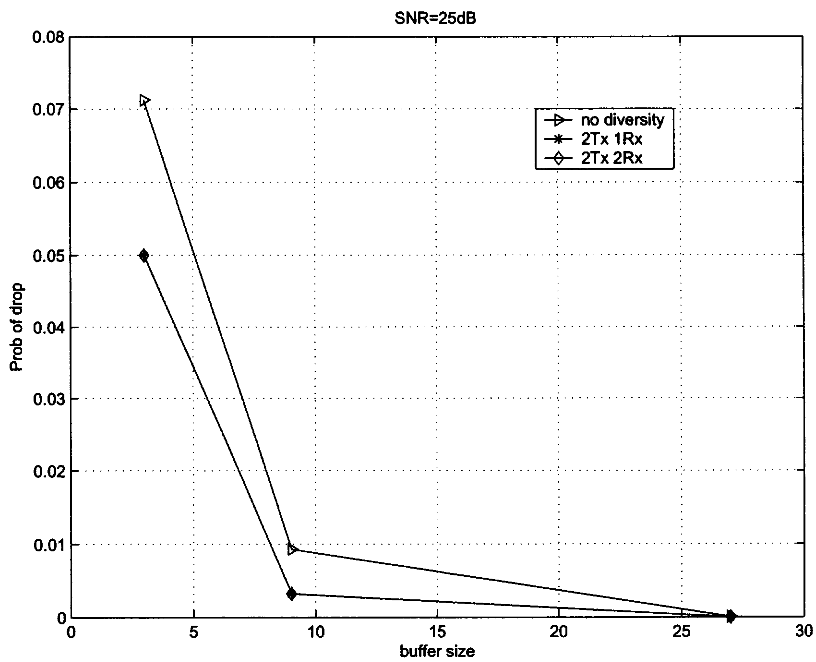

Figure 2.12 Drop probability vs. buffer size, analytical results (SNR=25dB, $\alpha = 0.6$, $0 < \mu_{no} < \mu_{stbc} < \mu_{2t2r}$)

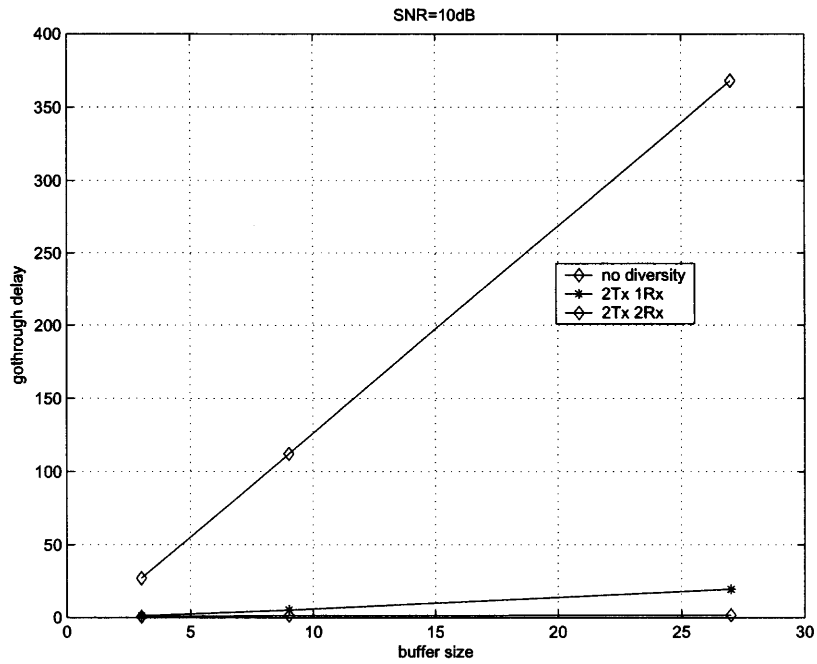

Figure 2.13 Go through delay vs. buffer size, analytical results (SNR=10dB, $\alpha = 0.5$, $\mu_{no} < \mu_{stbc} < 0 < \mu_{2t2r}$)

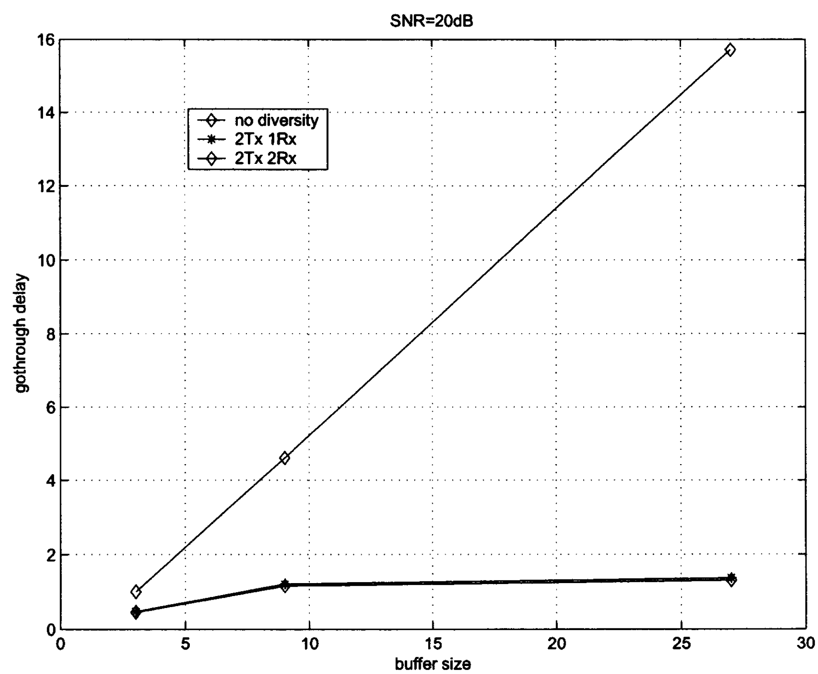

Figure 2.14 Go through delay vs. buffer size, analytical results (SNR=20dB, $\alpha = 0.8$, $\mu_{no} < 0 < \mu_{stbc} < \mu_{2t2r}$)

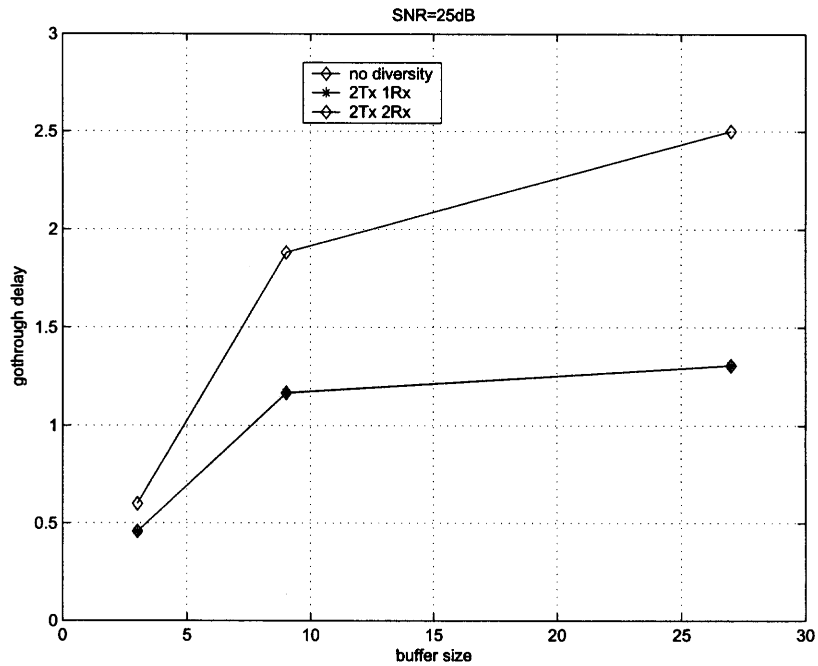

Figure 2.15 Go through delay vs. Buffer size, analytical results (SNR=20dB, $\alpha = 0.5$, $0 < \mu_{no} < \mu_{stbc} < \mu_{2t2r}$)

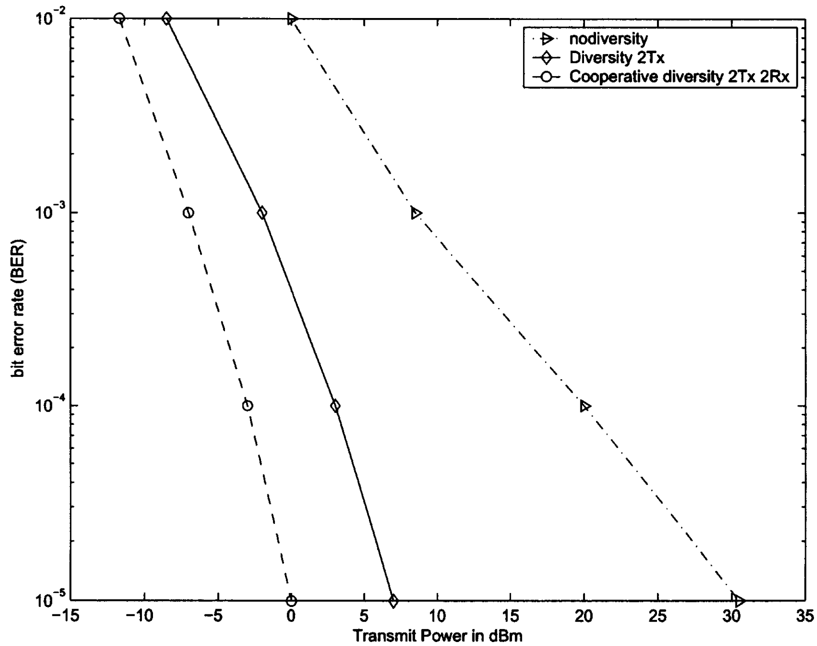

Figure 2.16 Bit error rate vs. transmission power using various of transmission methods

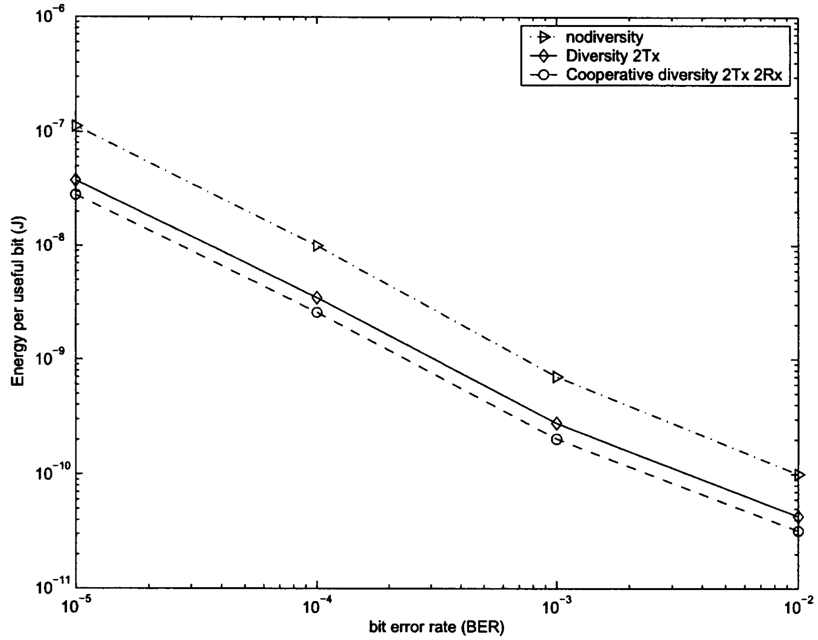

Figure 2.17 The energy per bit vs. bit error rate using various of transmission methods

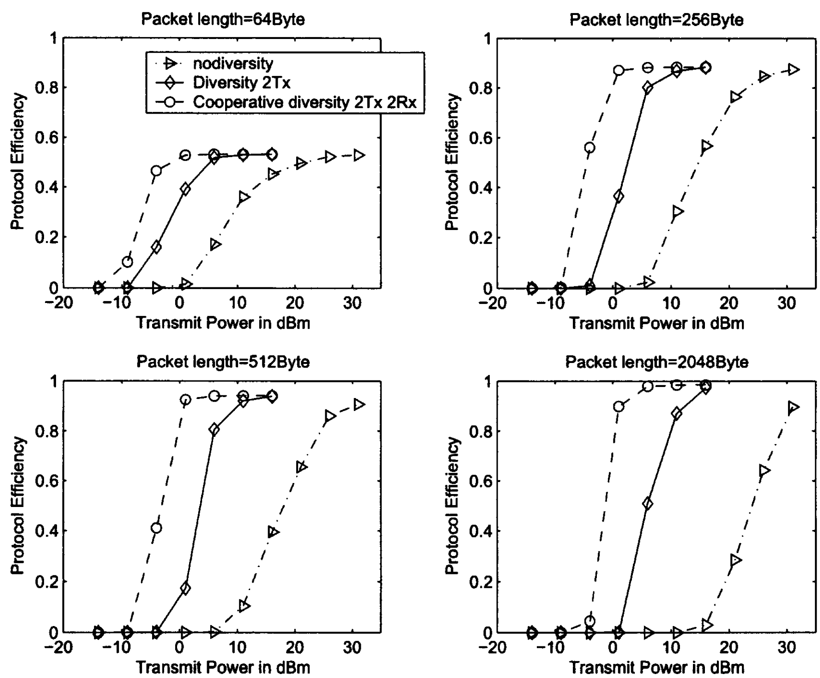

Figure 2.18 The protocol efficiency η_{pe} vs. mean transmission power for 64 byte packets using various of transmission methods

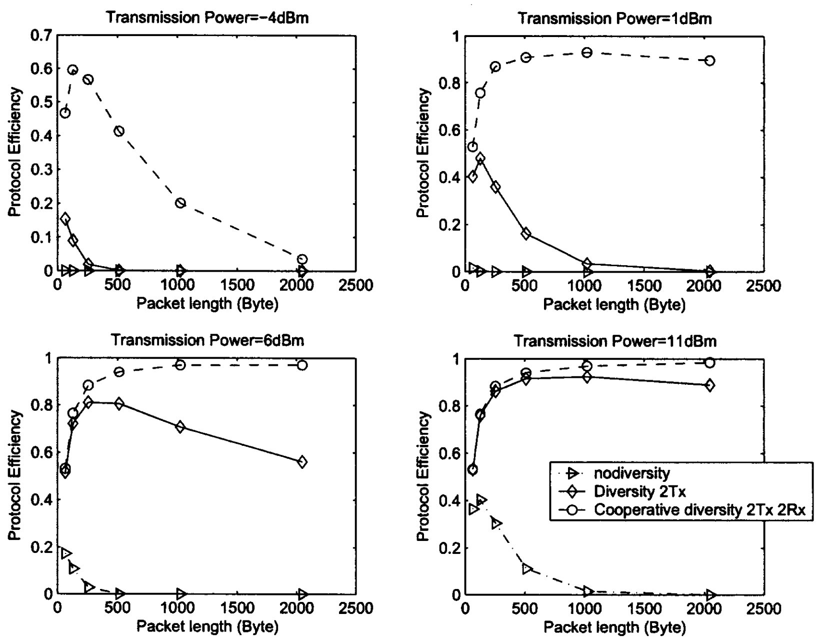

Figure 2.19 The protocol efficiency η_{pe} vs. packet size for various transmission power

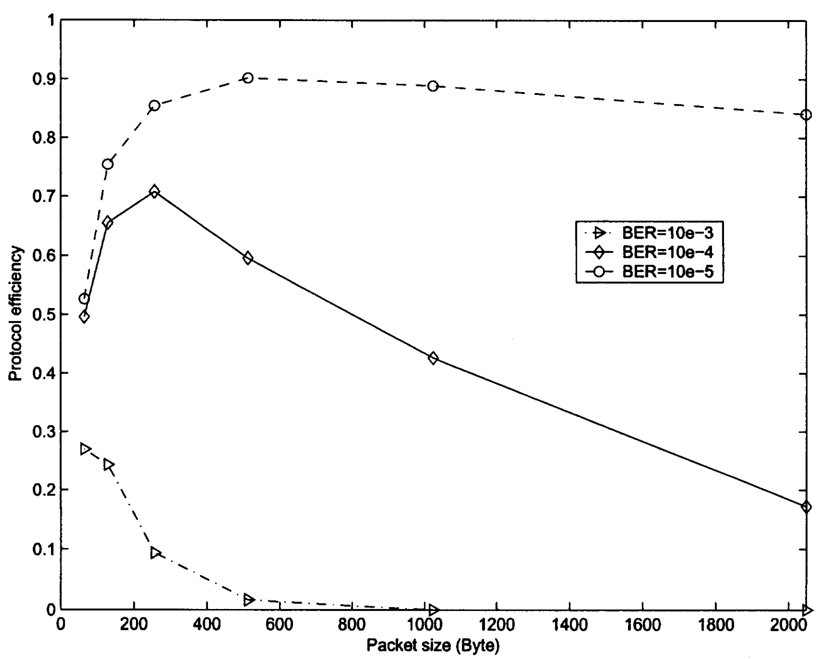

Figure 2.20 The protocol efficiency η_{pe} vs. packet size for various BER

transmission power, the protocol efficiency increases relatively fast up to a certain level, which depends on the transmission method chosen in the network. An increased transmission power is equivalent to a smaller BER, which result in a better protocol efficiency. Further more, it is important to note that if the transmission power reach a certain level (approximately -1 dBm, 5 dBm and 31 dBm for the new scheme, transmission diversity method and the traditional approach for 512 Byte packets) , only a marginal increases of protocol efficiency is reported. One can observe that the protocol efficiency remains smaller for 64 Byte packets and a little higher using 2048 Byte packets For the same protocol efficiency, the new scheme has the lowest transmission power level.

In Figure 2.19, the protocol efficiency η_{pe} vs. packet length is shown for different transmission schemes. At the same transmission power level, the new scheme provide the highest protocol efficiency. The figure clearly shows that there is an optimal packet size providing the highest protocol efficiency for different transmission schemes. In Figure 2.20, the protocol efficiency curve indicates for the higher BER, which is equivalent to low transmission power, that smaller packets have the better performance; for low BER, the larger packets have the best efficiency. For example, when the BER is 10^{-5}, the optimal packet size is about 500 Bytes. First, The protocol efficiency is mainly influenced by the MAC (hearder, trailer and control packet) for small packet case. For long packets the MAC plays a minor role, but long packets will be corrupted with high probability, resulting in retransmissions.

2.6 Conclusions

In this chapter,the cooperative space-time coding and quality-based cooperative routing for cross layer design in multi-hop wireless sensor networks is introduced. Selected multiple nodes according to the link quality act as the transmitting and receiving antenna array. The linear space-time code is used to provide transmission diversity, and the sink uses a maximum ratio combining (MRC) together with its neighbors to make symbol decision.

One can find that the new scheme is beneficial for overcoming the mutilpath fading and reducing the interference (lower power for same BER requirement). The results indicate that the cooperative scheme is energy efficient. The protocol harmonization scheme is used to reduce energy consumption for signal transmitting. It is demonstrated that data link layer and physical layer correlate. An inappropriately chosen transmission power may result in energy waste. The results show that there is an optimal transmission power for each packet size and different transmission schemes. The new scheme provide the best protocol efficiency at the same transmission power level. Furthermore, the result indicate, that packets should be as large as possible to save energy for low BERs. This mechanism would be extremely useful for non real time data.

CHAPTER 3

DIFFERENTIAL SPACE-TIME BLOCK CODING FOR COOPERATIVE RELAYS IN SENSOR NETWORKS

3.1 Motivation

Wireless sensor networks can efficiently provide environment monitoring for many civil and military applications. Traditionally, in wireless data routing, the routing protocols do not penetrate into the physical layer, and the physical layer research ignores some degree of design freedom avoidable at the networking layer. Recently, parallel wireless relay schemes have been introduced into wireless sensor networks [29] [37]. The parallel relays, using space-time modulation and cross-layer design, are the contender against the traditional routing protocol.

In a typical sensor network, information collected by sensors needs to be transmitted to a remote processor center (the collector). If the collector is far away, the information may first be transmitted to a relay node, then multi-hop routing will be used to forward the information to its final destination, as shown in Figure 3.1. Assuming a source can be heard by the multiple neighbor nodes simultaneously, this method can select several nodes as the relay nodes to bring cooperative diversity into the routing process. In doing so, each relay node receives the signal transmitted from the source and retransmit the signal *in parallel* via STBC to the next hop. After several hops of relay, the destination receives a superimposed version of the transmitted symbols. With the space diversity provided by the relay nodes, the destination is then able to detect the original symbol sequence transmitted from the source.

Various STBC communication approaches have been proposed [28] [36]. The achievable throughput on wireless fading channel can be systematically increased by using multiple transmitting and/or receiving antennas. However coherent detection method needs to estimate and track the time-varying channel, resulting in the increasing system complexity as the number of the parallel relays grows [38]. Huges [39] and Hochwald and Sweldens [40] independently proposed differential unitary space-time modulation (DUSTM). Differential STBC communications avoid the tracking complexity through the use of noncoherent detection over the block fading channel [41].

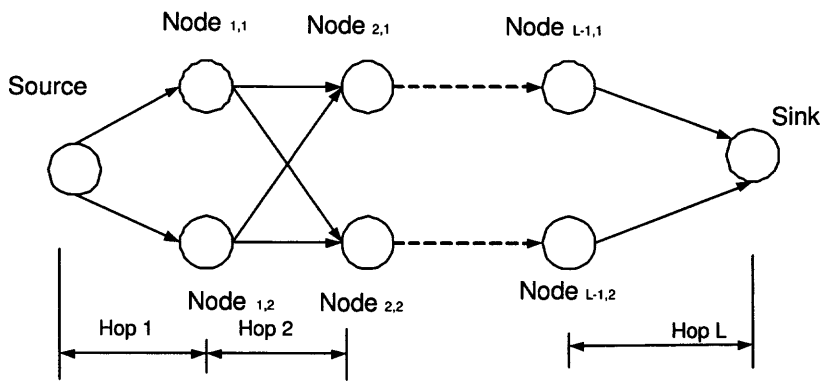

Figure 3.1 A multihop sensor network with cooperative relays.

3.2 Differential Space-Time Block Codes for Wireless Relays

In this work, consider a multi-hop wireless sensor network over a block fading channel, where the channel coefficients between the source node and the relay nodes are statistically independent, but remain unchanged within T symbol periods. The source node sends a set of data $\mathbf{d}$, a $T \times 1$ vector over multiple time-slots using a differential scheme. Specifically, for $T = 2$, given $\mathbf{s}_{0,0} = \begin{bmatrix} 1 & 0 \end{bmatrix}^T$ as the initial symbol, the sequential differential coded symbols are generated as $\mathbf{s}_{0,t} = \mathbf{D}_{0,t}\, \mathbf{s}_{0,t-1}$, where

$$\mathbf{D}_t(\mathbf{d}) = \frac{1}{\sqrt{2}} \begin{bmatrix} d_1 & d_2 \\ -d_2^* & d_1^* \end{bmatrix}$$

contains data $\mathbf{d}$.

At the first hop, 2 nodes ($\text{Node}_{1,1}$ and $\text{Node}_{1,2}$) are chosen that act as the relay nodes, as shown in Figure 3.1. The relay nodes selection is based on the link quality [34] over T

symbol interval. The received signal corrupted by channel and noise is contained in a $T \times 2$ matrix, i.e.

$$\mathbf{X}_1 = \rho\, \mathbf{s}_0\, \mathbf{h}_1^T + \mathbf{W}_1 \tag{3.1}$$

where ρ^2 is the signal to noise ratio, $\mathbf{h}_1$ is the 2×1 channel coefficient vector between source node and the first hop relay nodes, the $T \times 2$ noise matrix $\mathbf{W}_1$ is normalized complex gaussian distributed (with i.i.d. elements). Specifically, for one step differential STBC, two consecutive received signal matrices at these relay nodes are used to recover the information matrix $\mathbf{D}_t$ at each time block. Assume that the channel remains unchanged within $T = 2 \times 2$ symbol periods, then the received data matrices are,

$$\begin{aligned} \mathbf{X}_{1,t-1} &= \rho\, \mathbf{s}_{0,t-1}\, \mathbf{h}_1^T + \mathbf{W}_{1,t-1} \\ \mathbf{X}_{1,t} &= \rho\, \mathbf{s}_{0,t}\, \mathbf{h}_1^T + \mathbf{W}_{1,t} \end{aligned} \tag{3.2}$$

From (3.2), one obtains that

$$\mathbf{X}_{1,t} = \mathbf{D}_{0,t}\, \mathbf{X}_{1,t-1} - \mathbf{D}_{0,t}\, \mathbf{W}_{1,t-1} + \mathbf{W}_{1,t}$$

Because the noise matrices at different time blocks are independent and have i.i.d. entries, one can get

$$\mathbf{X}_{1,t} = \mathbf{D}_{0,t}\, \mathbf{X}_{1,t-1} + \sqrt{2}\mathbf{W}'$$

where $\mathbf{W}'$ is a 2×2 equivalent noise matrix whose elements are complex Gaussian with mean 0 and variance 0.5 per dimension. In this differential receiver equation, $\mathbf{X}_{1,t-1}$ can be treated as the known channel matrix for the system transmitting $\mathbf{D}_{0,t}$ with noise variance 2. Ignoring the dependence of the noise on the transmitted signal, the sub-optimal differential decoder is

$$\hat{\mathbf{D}}_{0,t} = \arg \min_{\mathbf{D}} ||\mathbf{X}_{1,t} - \mathbf{D}_{0,t}\, \mathbf{X}_{1,t-1}||^2 \tag{3.3}$$

These relay nodes, after decoding the received signals and get $\hat{\mathbf{d}}$, according the estimated data, relay their data to the second hop relay nodes in a differential way. That is, an identity matrix is sent by these relay nodes to initialize the transmission. The data matrices are then differentially encoded and sent. The transmitted signal matrices can be written as

$$\begin{cases} \mathbf{S}_{1,0} = \mathbf{I} \\ \mathbf{S}_{1,t} = \mathbf{D}_{1,t}\,\mathbf{S}_{1,t-1} \end{cases} \tag{3.4}$$

where $\mathbf{D}_{1,t} = \hat{\mathbf{D}}_{0,t}$. The received data at the second hop relay nodes ($\text{Node}_{2,1}$ and $\text{Node}_{2,2}$) are

$$\mathbf{X}_2 = \rho\,\mathbf{S}_1\,\mathbf{H}_{12} + \mathbf{W}_2$$

where $\mathbf{H}_{12}$ is the channel coefficient matrix between the first hop relay nodes and the second hop relay nodes.

Similar to the first hop, these relay nodes generate their transmitted matrix

$$\mathbf{D}_{2,t} = \hat{\mathbf{D}}_{1,t} = \arg\min_{\mathbf{D}} \|\mathbf{X}_{2,t} - \mathbf{D}_{1,t}\,\mathbf{X}_{2,t-1}\|^2 = \begin{bmatrix} \mathcal{R}_1 & \mathcal{R}_2 \\ -\mathcal{R}_2^* & \mathcal{R}_1^* \end{bmatrix} \tag{3.5}$$

where

$$\begin{aligned} \begin{bmatrix} \mathcal{R}_1 & \mathcal{R}_2 \end{bmatrix} &= \begin{bmatrix} x_{1,2t+1} & x_{1,2t+2}^* \end{bmatrix} \begin{bmatrix} x_{1,2t-1}^* & x_{1,2t}^* \\ x_{1,2t} & -x_{1,2t-1} \end{bmatrix} \\ &+ \begin{bmatrix} x_{2,2t+1} & x_{2,2t+2}^* \end{bmatrix} \begin{bmatrix} x_{2,2t-1}^* & x_{2,2t}^* \\ x_{2,2t} & -x_{2,2t-1} \end{bmatrix} \end{aligned} \tag{3.6}$$

then relay their data to the next hop

$$\begin{cases} \mathbf{S}_{2,0} = \mathbf{I} \\ \mathbf{S}_{2,t} = \mathbf{D}_{2,t}\,\mathbf{S}_{2,t-1} \end{cases} \tag{3.7}$$

This process is repeated until the transmitted signals finally reach the destination. For a relay system with L hops, the received data at the destination is

$$\mathbf{y} = \rho\, \mathbf{S}_{L-1}\, \mathbf{h}_{L-1,s} + \mathbf{w}_s$$

where $\mathbf{h}_{L-1,s}$ is the 2×1 channel vector between the $(L-1)$th hop relay nodes and the destination.

$$\mathbf{y}_{t-1} = \rho\, \mathbf{S}_{L-1,t-1}\, \mathbf{h}_{L-1,s} + \mathbf{w}_{s,t-1} \quad (3.8)$$

$$\mathbf{y}_{t} = \rho\, \mathbf{S}_{L-1,t}\, \mathbf{h}_{L-1,s} + \mathbf{w}_{s,t} \quad (3.9)$$

The differential decoder follows the decision rule,

$$\hat{\mathbf{D}}_{L-1,t} = \arg\min_{\mathbf{D}} \|\mathbf{y}_t - \mathbf{D}_{L-1,t}\, \mathbf{y}_{t-1}\|^2 \quad (3.10)$$

The orthogonal structure of STBC, leads to data symbols decoupling, hence the above suboptimal differential decoder has linear complexity [42].

At the sink node, write the received signal as: $\mathbf{y}_{t-1} = [\ y_{t-1}(1) \quad y_{t-1}(2)\ ]^T$ and $\mathbf{y}_t = [\ y_t(1) \quad y_t(2)\ ]^T$ Thus,

$$\begin{aligned} \mathcal{R}_1 &= y_t(2) y_t^*(1) + y_{t-1}^*(2) y_{t-1}(1) \\ &= \left(|h_{L-1,s}(1)|^2 + |h_{L-1,s}(2)|^2\right) \cdot d_{L-1}(1) + \mathcal{N}_1 \end{aligned} \quad (3.11)$$

and

$$\begin{aligned} \mathcal{R}_2 &= y_t(2) y_{t-1}^*(1) - y_{t-1}^*(2) y_t(1) \\ &= \left(|h_{L-1,s}(1)|^2 + |h_{L-1,s}(2)|^2\right) \cdot d_{L-1}(2) + \mathcal{N}_2 \end{aligned} \quad (3.12)$$

The detector then selects the constellation vector that is closest to $(\mathcal{R}_1\ \mathcal{R}_2)$. The combination of the transmission, relay, receiving and decoding from the source to the destination appears to higher layers as a virtual bit pipe with a bit error rate (P_e).

3.3 Energy Consumption

At a sensor node, use E_s to denote the energy needed to sense data (one bit), E_p to denote the energy needed for data processing (one bit), and E_{Rx}/E_{Tx} to denote the energy needed for receiving and transmitting the one bit data, respectively.

Assume the E_s, E_p are the same for all methods. This section will focus on the E_{Rx} and E_{Tx}. The energy needed to receive a bit E_{Rx} accounts for the receiver electronics energy dissipation. The energy needed to transmit a bit E_{Tx} consists of two parts: the energy dissipation of the transmitter electronics E_{txe}, and the the RF transmit energy E_{RF}, assume that $E_{txe} = E_{Rx}$

The energy per bit to noise ratio at the receiver is [2]

$$\frac{E_b}{N_0} = \frac{P_{RF}}{P_l \alpha} \cdot \frac{1}{W N_t N_r}$$

where P_{RF} is the RF transmission power, P_l is the large scale path loss, α is the average attenuation factor due to fading, W is the signal bandwidth, N_t is the thermal noise and N_r is the noise at the receiver known as the noise figure. In general, $P_l \propto \frac{1}{4\pi d^k}$, $2 \leq k \leq 4$.

The transmit power P_{RF} can be written as

$$P_{RF} = P_l \alpha W N_t N_r \frac{E_b}{N_0} \tag{3.13}$$

The RF energy needed for transmitting a bit is

$$E_{RF} = P_{RF} \cdot T$$

where P_{RF} is the transmission power and $T = \frac{W}{R}$ is the duration of the data transmission. The assumed parameters are given in table 3.1.

The total energy consumption for a single node is

$$E = E_s + E_p + E_{Rx} + E_{txe} + E_{RF}$$

Table 3.1 Assumed Parameter for Multihop Relay Sensor Networks

Parameter	Value
Fade margin and Pass loss $P_l\alpha$	70dB
Thermal noise at collector N_t	-174dBm
Receiver noise at collector N_r	10dB
Signal bandwidth W	1MHz
Data rate R	1Mbps

Since E_s and E_p are needed only at the source node, assume the E_s and E_p are the same for different relay methods, so E_s and E_p can be ignored. The the total energy used for data transmitted and relayed in the whole network are:

$$E_{total,s} = LE_{Rx} + LE_{txe} + LE_{RF} = LE_{RF} + 2LE_{Rx}$$

and

$$E_{total,c} = (2L-1)E_{Rx} + (2L-1)E_{txe} + LE_{RF} = LE_{RF} + (4L-2)E_{Rx}$$

3.4 Simulation Results

To observe the performance of the differential STBC for cooperative relays method, this chapter compared it with the single relay method through simulations. In the simulation system, the channel model is assumed to be a block flat Rayleigh fading. Each packet contains $Len = 128$ symbol periods. Assume there are $L = 3$ hops from the source to the destination, and at each hop, two nodes are selected for packets relay. The source node's buffer with infinite capacity is feeded by Poisson sources with density λ, the system simulation time equals to 10000 τ.

Figure 3.2 compares the performance of the above two relay methods in terms of bit error probability. The data symbol is BPSK. In the figure, the results show that the cooperative relays can provide lower BER than the traditional single relay method.

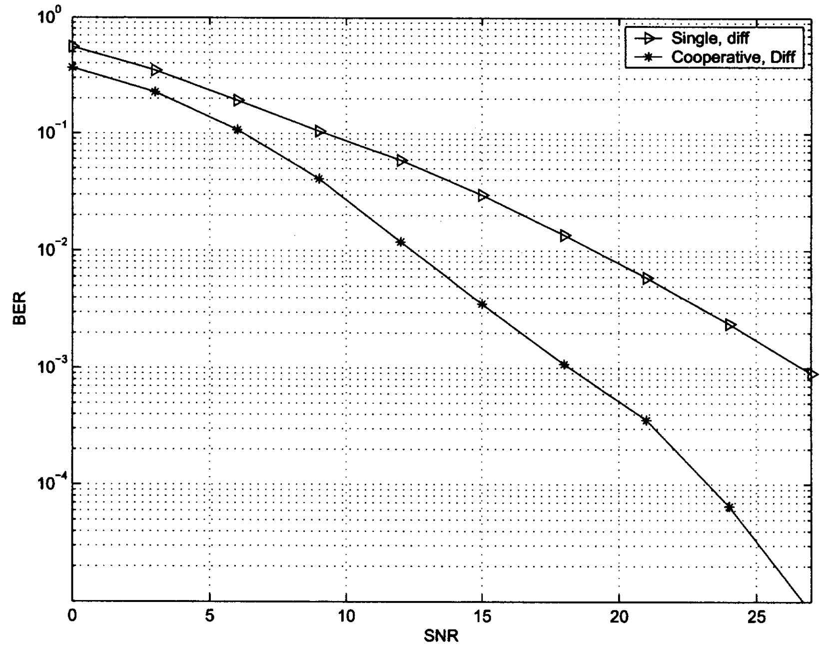

Figure 3.2 Performance of single relay and cooperative relays with BPSK data symbols.

Figure 3.3 shows the probability of packet successful transmission vs. SNR. The diversity gain of the cooperative relays at P_{ST} of 0.9 is about 9 dB better than a single relay scheme.

Figure 3.4 shows μ versus the traffic load when SNR=24dB, the value of μ decreases while the traffic load increases. The system is stable as long as $\mu > 0$. Figure 3.5 shows the throughput versus the traffic load for different approaches. The cooperative relay approach has a better performance than the single relay one. If $\mu > 0$, the throughput equals to the traffic load; if $\mu \leq 0$, the carried load (throughput) equals the capacity of the system. The delay performance is shown in Figure 3.6 as a function of the traffic load. The simulation results demonstrate that the new scheme outperforms the traditional one. It is also observed that when μ is greater than zero, they both can deliver packets and the cooperative one can provide smaller delay because of μ_c is greater than μ_s. When the traffic load increases to a certain level, say about 0.9, the cooperative one still works, but the traditional one walks with disaster (the delay increases to infinity).

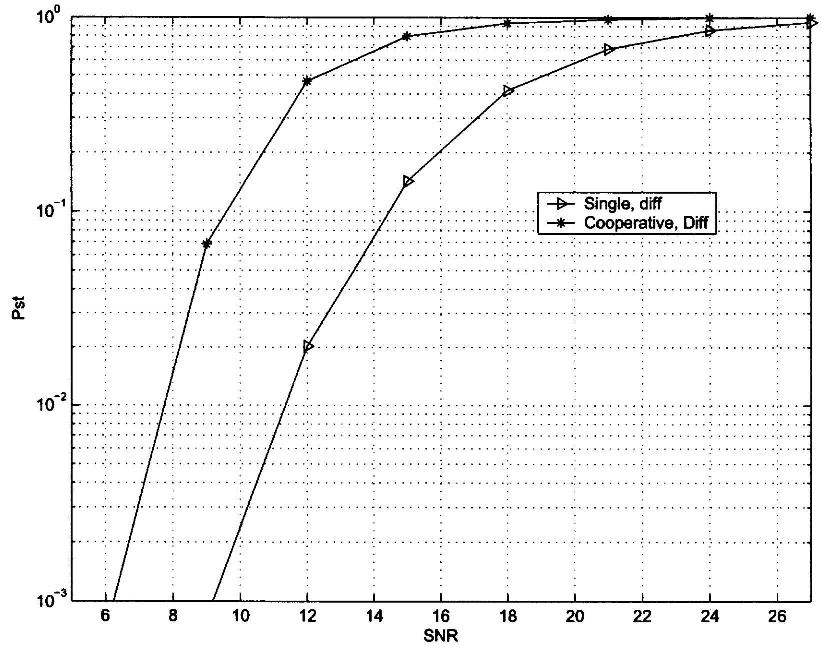

Figure 3.3 Probability of packet successfully transmission vs. SNR.

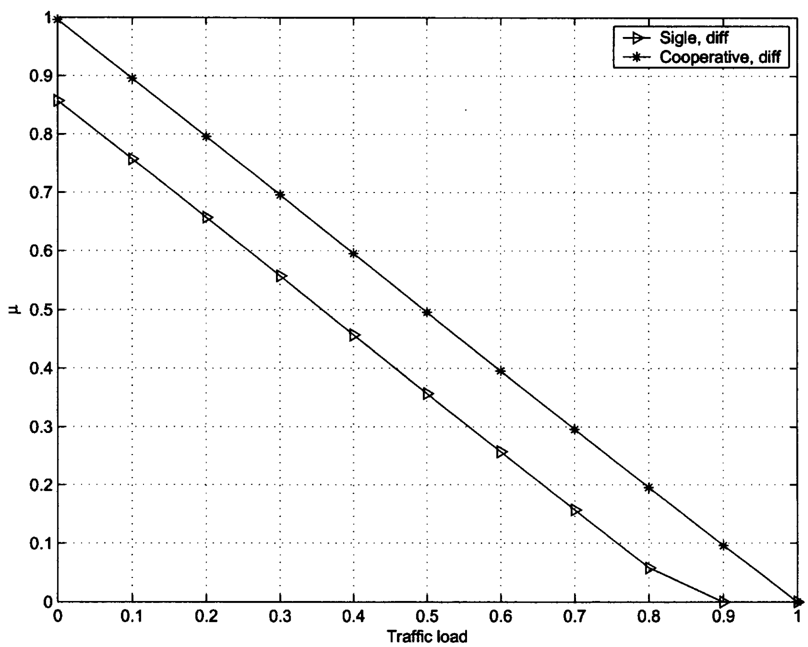

Figure 3.4 μ vs. trafficload

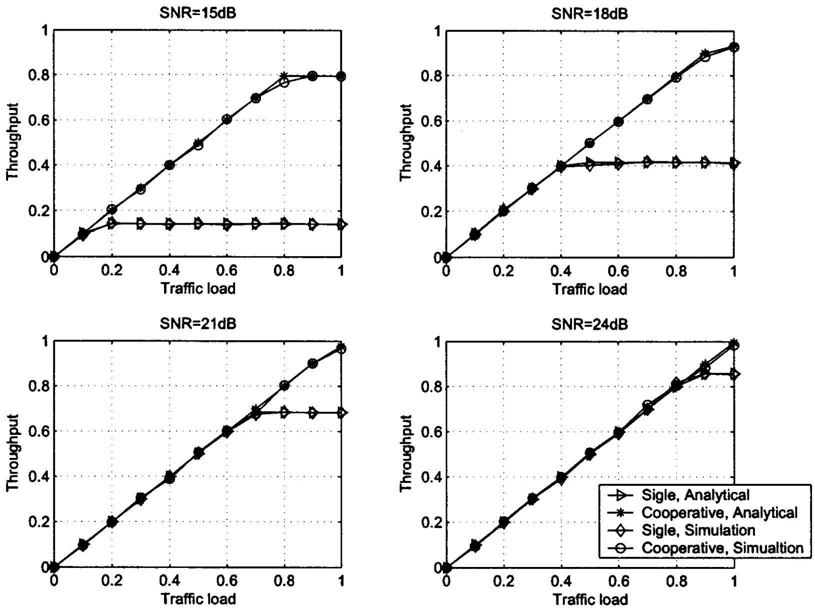

Figure 3.5 Throughput vs. traffic load, simulation results

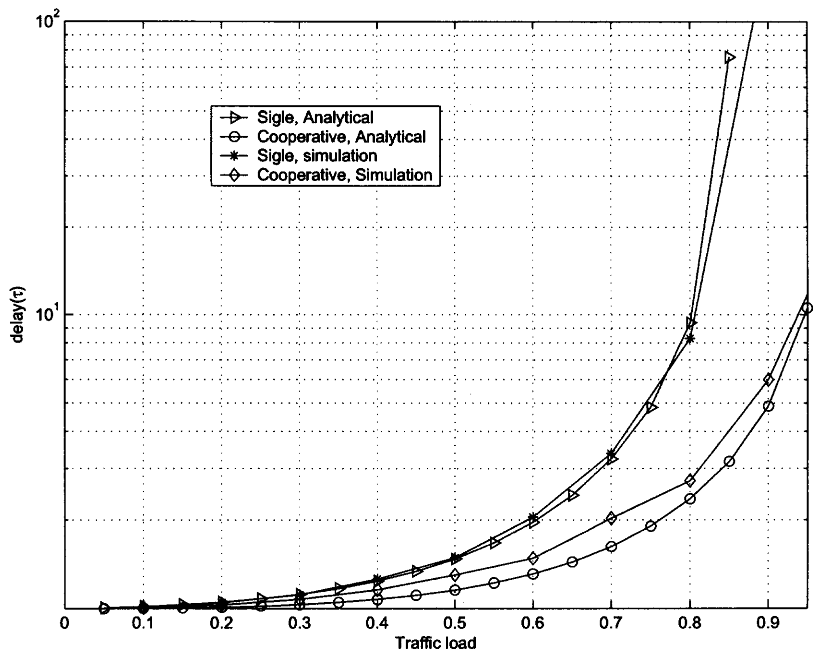

Figure 3.6 Delay vs. traffic load, analytical and simulation results (SNR=24dB)

The go through delay performance is shown in Figure 3.7 to Figure 3.9 as a function of the buffer size. When $\mu_s < \mu_c < 0$, the go through delay increases when buffer size increases, they both go to infinity, and cooperative one has the better performance. When $\mu_s < 0 < \mu_c$, go through delay increases when buffer size increases, the delay of single method goes to infinity, and the cooperative one goes to a constant value. When $0 < \mu_s < \mu_c$, the go through probability increases when buffer size increases, and both of them go to a finite value. The cooperative one has the smaller go through delay.

Figure 3.10 to Figure 3.12 show the drop probability versus buffer size. When $\mu_s < \mu_c < 0$, the probability of drop decreases when buffer size increases, they both drop to a certain level, and cooperative one has the better performance. When $\mu_s < 0 < \mu_c$, cooperative method drops to 0 and single method drops to a certain level. When $0 < \mu_s < \mu_c$, both of them drop to 0, but cooperative drops much faster than the single one. The simulation results demonstrate that the proposed scheme has smaller drop probability than the traditional one.

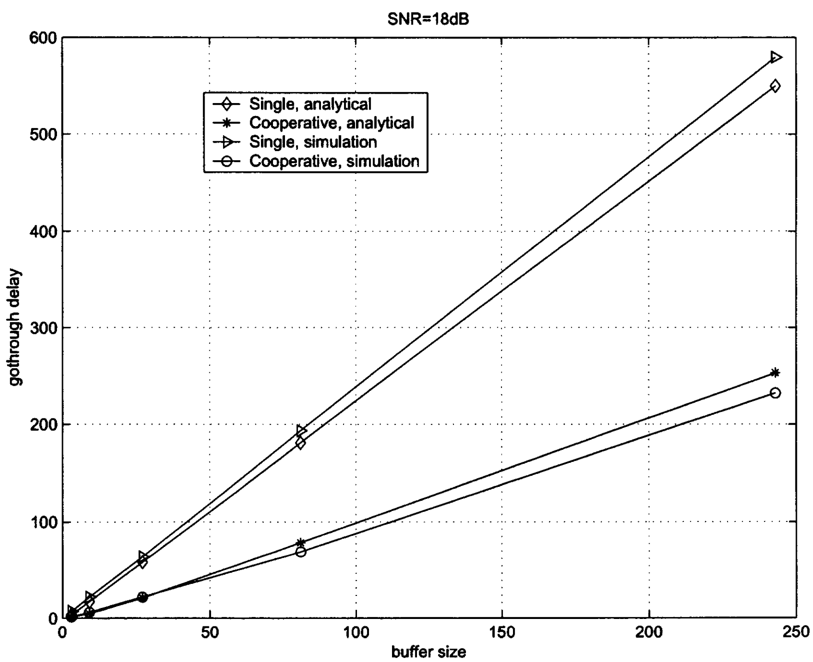

Figure 3.7 Go through delay vs. buffer size, analytical and simulation results (SNR=18dB, $\alpha = 1$, $\mu_s < \mu_c < 0$)

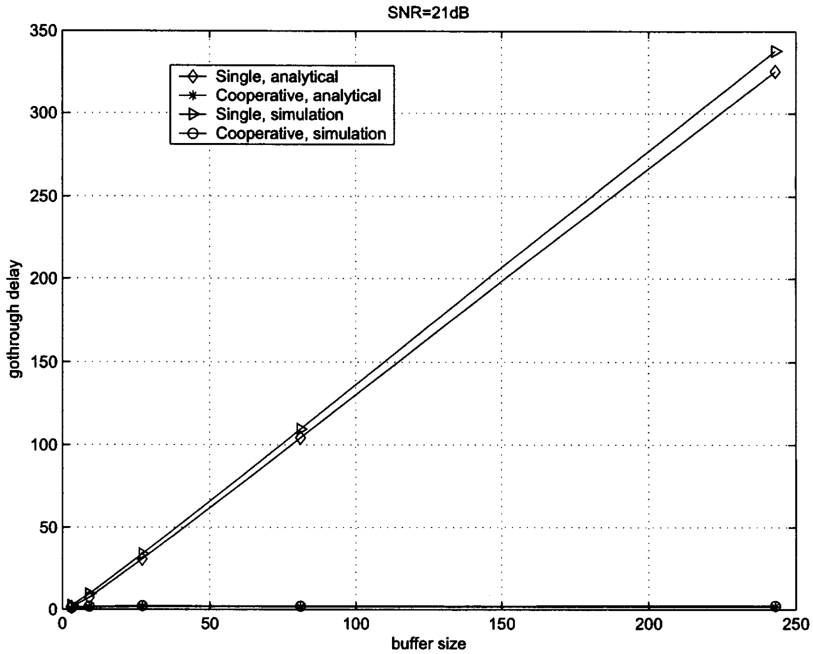

Figure 3.8 Go through delay vs. buffer size, analytical and simulation results (SNR=21dB, $\alpha = 0.8$, $\mu_s < 0 < \mu_c$)

Figure 3.13 show the BER vs. RF transmitting power for different relay methods. It is shown that to achieve the same BER, cooperative one need less RF transmitting power, that is because the diversity provided by DSTBC can overcome the fading.

The RF energy vs. BER is shown in Figure 3.14, and Figure 3.15 shows the total energy needed vs. BER. There is a threshold or a critical point, when total energy is higher than that point (the blue curve is above the red curve), the cooperative relay method has lower BER, and the probability of successful transmission is higher. Therefore the cooperative method has better performance. When the total energy is lower than that point (the blue curve is under the red curve), the single relay method can provide lower BER, and then the better performance.

Figure 3.16 shows the delay and throughput performance vs. the traffic load when total energy is higher than the point, both methods use the same total energy, and cooperative method has better performance (higher throughput and lower delay). Figure

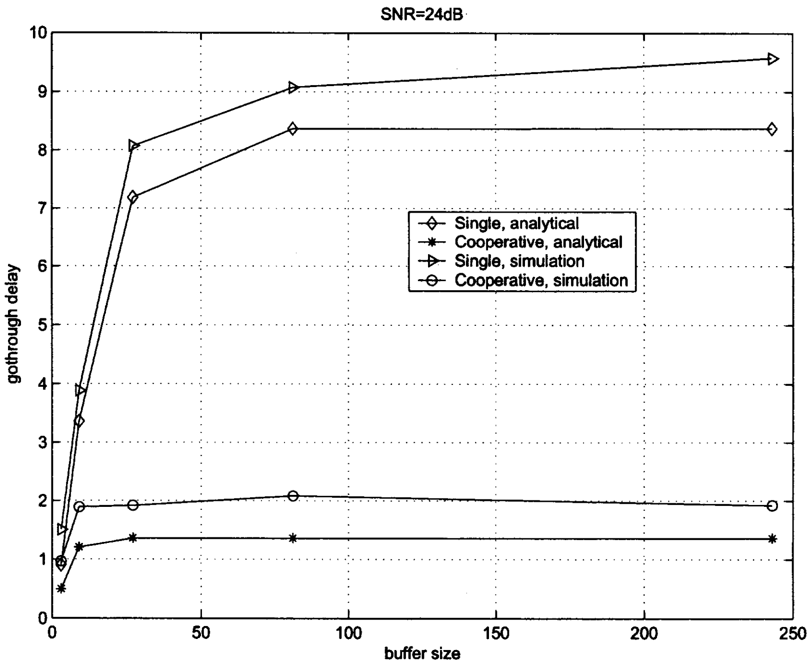

Figure 3.9 Go through delay vs. buffer size, analytical and simulation results (SNR=24dB, $\alpha = 0.8, 0 < \mu_s < \mu_c$)

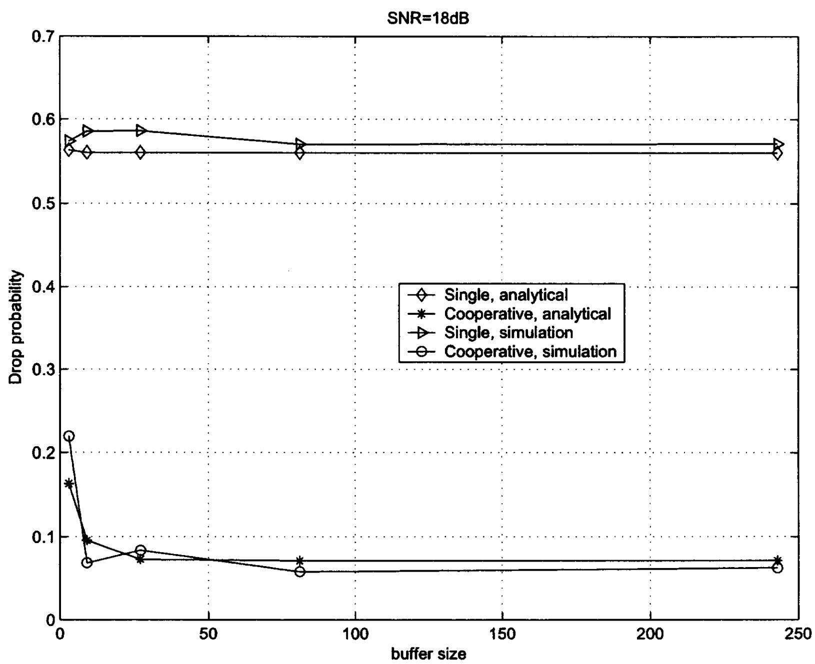

Figure 3.10 Drop probability vs. buffer size, simulation and analytical results (SNR=18dB, $\alpha = 1, \mu_s < \mu_c < 0$)

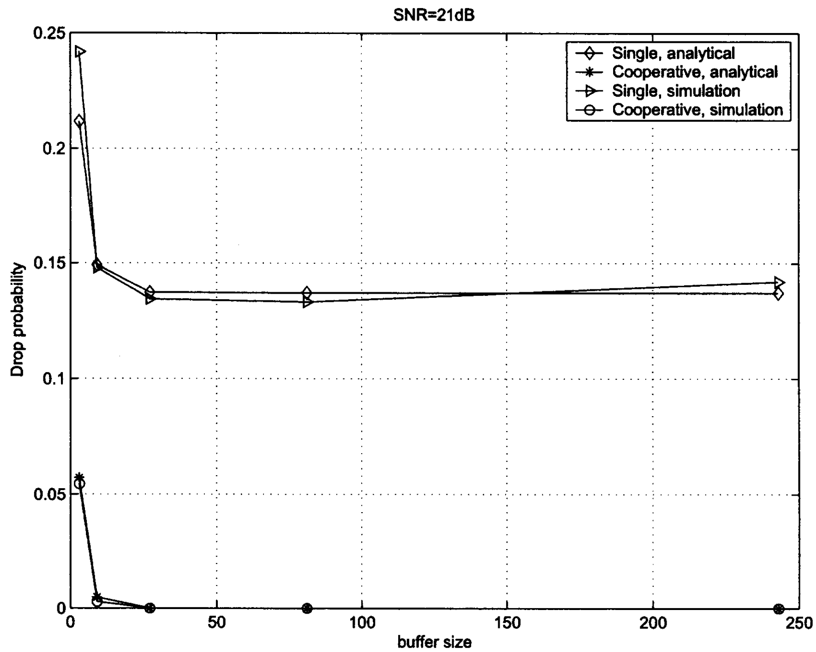

Figure 3.11 Drop probability vs. buffer size, simulation and analytical results (SNR=21dB, $\alpha = 0.8$, $\mu_s < 0 < \mu_c$)

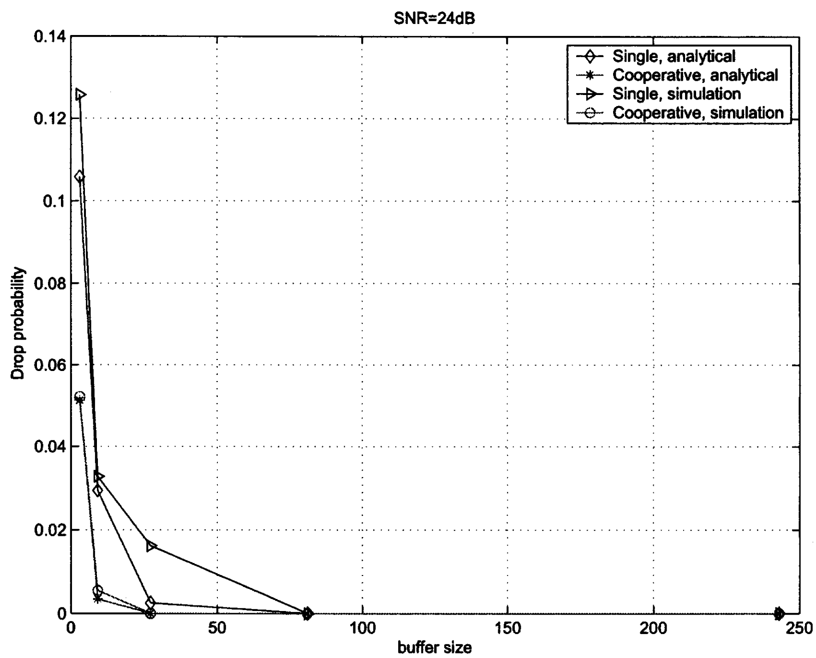

Figure 3.12 Drop probability vs. buffer size,simulation and analytical results (SNR=24dB, $\alpha = 0.8$, $0 < \mu_s < \mu_c$)

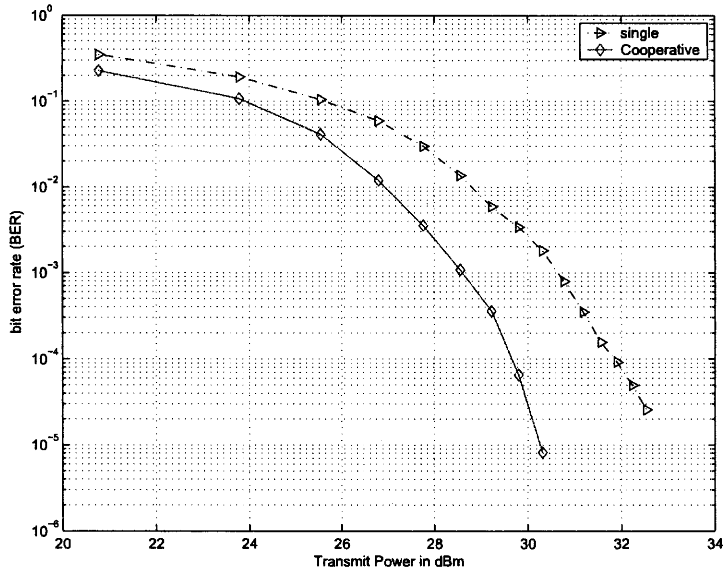

Figure 3.13 BER vs. RF transmitting power

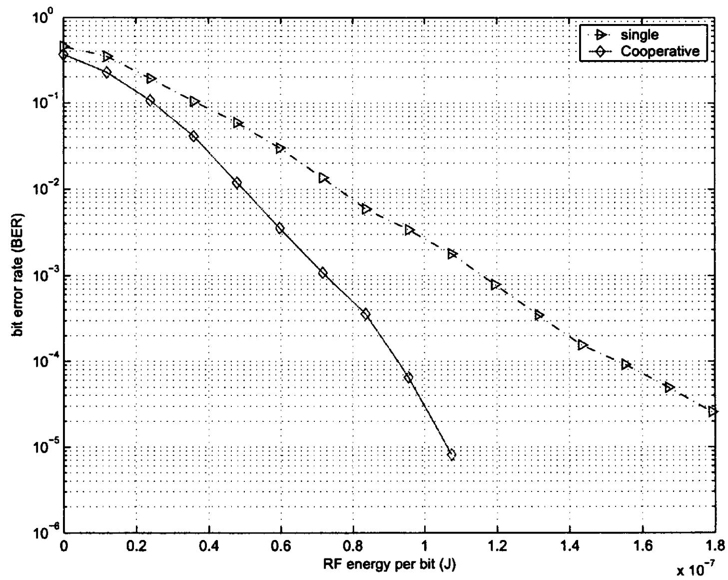

Figure 3.14 BER vs. RF transmitting energy

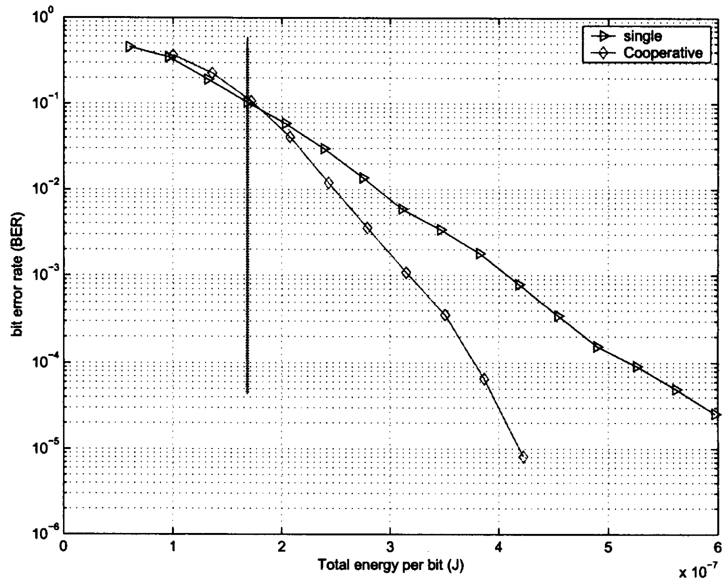

Figure 3.15 BER vs. total energy used

3.17 shows the delay and throughput performance vs. the traffic load when total energy is lower than the point, both methods use the same total energy, and single relay method has better performance (higher throughput and lower delay). Since the throughput are pretty low, both of them are unacceptable in high traffic load case.

When both method use the same amount of total RF power (RF energy), the cooperative method is better. When the same total energy consumption is consided, since more nodes participate the data relay, more receiving energy and transmitting energy used for cooperative method, to keep the same total amount of energy, the cooperative scheme should decrease the RF power of cooperative method, it introduce some BER loss. Since the BER curves are not parallel to each other, the cooperative one decrease much faster, the BER performance is also better even after the loss, therefore the cooperative one has better performance.

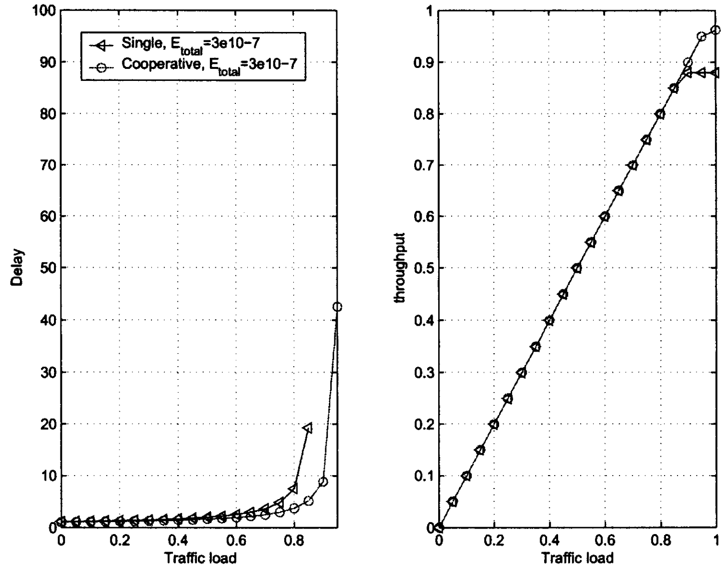

Figure 3.16 Delay and throughput vs. traffic load ($E_{total,s} = E_{total,c} = 3.0 \times 10^{-7} J$)

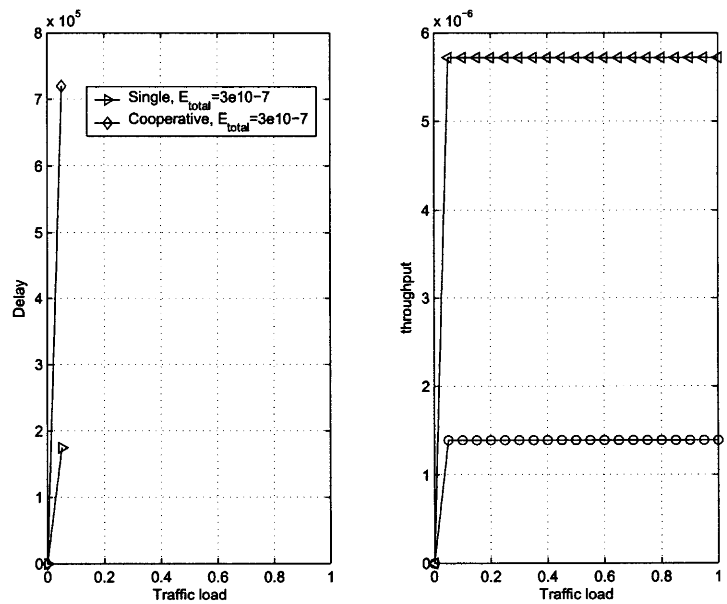

Figure 3.17 Delay and throughput vs. traffic load ($E_{total,s} = E_{total,c} = 1.7 \times 10^{-7} J$)

3.5 Conclusions

This chapter introduce the differential space-time coding with cross layer design for cooperative relay in multi-hop wireless sensor networks. The proposed method can effectively overcome the multipath fading without channel tracking. The analytical and simulation results indicate significant system improvements in terms of bit error rate and the packet successful transmission probability. Consequently, the network throughput and the end-to-end delay are also improved considering the traditional method. Moreover, the new approach leads to lower computation complexity for sensor nodes.

CHAPTER 4

IMPACT OF NETWORK RESOURCE CONSTRAINTS ON THE PERFORMANCE OF WIRELESS RELAY SENSOR NETWORKS

4.1 Motivation

One of the most important performance measures of a data network is the average delay required to deliver a packet from original to destination. Furthermore, delay consideration strongly influence the choice and performance of network algorithms, such as routing and flow control. For these reasons, it is important to understand the nature and mechanism of delay, and the manner in which it depends on the characteristics of the network. Throughput is another important performance.

Queueing theory is the primary methodological framework for analyzing network delay and throughput. It often uses required simplifying assumptions since more realistic assumption make meaningful analysis extremely difficult. For this reason, it is sometimes impossible to obtain accurate quantitative delay predication on the basis of queueing models. These models often provide a basis for adequate delay approximations, as well as valuable qualitative results and worthwhile insight.

Since all service facilities have finite resources, a system with finite buffer size is more practical than one with infinite buffer size. Moreover, the network resources of a tiny sensor node in sensor network is limited by the node's small size and low cost. For example, a node has limited power and energy due to the battery, limited computation ability due to the micro processor utilized, limited buffer size due to the small memory. The impact of the buffer size on the network performance is also should be carefully considered. When buffer size of a node is limited, some of the new arrival will be blocked when the buffer is full, so the drop probability (block probability) is a important performance to measure such a network system. Therefore, the end-to-end delay of the users which really come in the system is another major performance measure, and is called go through delay.

4.2 Performance Analysis Using Markov Chain Model and Skip Free Negative Process

The performance of system is analyzed from the view point of the network. In considering the packet pass through the network via the virtual bit pipe from the source to the sink, the system model is constructed via a Markov chain. Then the system throughput and delay are analyzed.

4.2.1 Markov Chain and Steady State Model

Consider a queueing system where packets arrive at random times for service. Define the system state as the number of data packets, which equals the packets waiting in queue (waiting in the buffer of the source node) plus packets undergoing service (transmission through the bit pipe), in the system. Define the transmission period for one packet as τ. The traffic load follows the Poisson distribution with rate λ, $N(t)$ is the number of new packets arriving in the interval $(0, t]$.

The probability that there are k data packets coming into the buffer during time τ is:

$$P\Big(N(t+\tau) - N(t) = k\Big) = \frac{(\alpha)^k}{k!} e^{-\alpha}, \tag{4.1}$$

where $\alpha = \lambda\tau$ is the average number of packet arrivals during transmission period τ. Assume that there is a buffer of infinite capacity for waiting packets [24]. Later a similar technique can be used in case of a finite buffer. The transition probability P_k (from i to $i+k$, except $i = 0, k = 0$) is

$$P_k = P_{i,i+k} = \frac{(\alpha)^k}{k!} e^{-\alpha} P_{FT} + \frac{(\alpha)^{k+1}}{(k+1)!} e^{-\alpha} P_{ST} \tag{4.2}$$

where $P_{ST} = (1 - P_e)^{Len}$ is the probability for successful transmission, Len is the length of the packet, and $P_{FT} = 1 - P_{ST}$ is the probability of the packet transmission failure.

The transition probability P_{-1} and P_0 are

$$P_{-1} = P_{i,i-1} = e^{-\alpha} P_{ST} \tag{4.3}$$

$$P_0 = P_{i,i} = e^{-\alpha} P_{FT} + \alpha e^{-\alpha} P_{ST} \tag{4.4}$$

The transition probability from state 0 to 0 is $P_{0,0} = P_{-1} + P_0$.

The system can be modeled as a Markov chain with states $(0, 1, 2, \cdots)$ and transition probabilities P_k, as shown in Fig. 4.1.

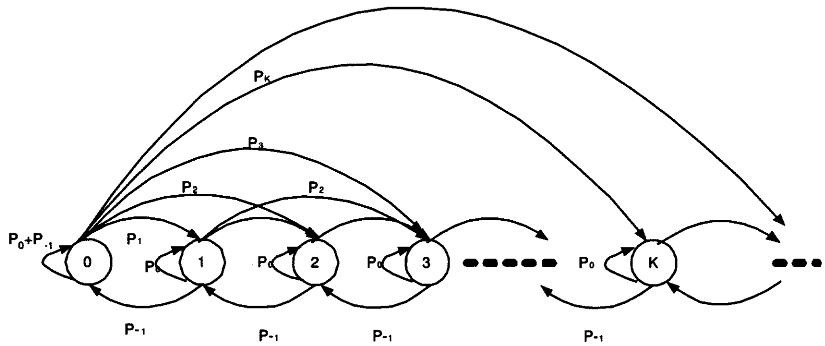

Figure 4.1 Markov chain model for packet transmission at given node

The corresponding transition probability matrix is

$$\mathbf{P} = \begin{pmatrix} P_0 + P_{-1} & P_{-1} & 0 & \cdots & 0 \\ P_1 & P_0 & P_{-1} & \cdots & 0 \\ P_2 & P_1 & P_0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \end{pmatrix}$$

and it is a skip free negative process [43]. Denote the stationary probability distribution of the whole system as $\boldsymbol{\pi} = [\pi_0 \; \pi_1 \cdots]^T$. Then

$$\boldsymbol{\pi}^T \mathbf{P} = \boldsymbol{\pi}^T$$

That is [44]

$$\begin{cases} \pi_0 = (P_{-1} + P_0)\pi_0 + \pi_1 P_{-1} \\ \pi_k = \sum_{r=0}^{k} \pi_r P_{k-r} + \pi_{k+1} P_{-1}, \quad k \geq 1 \end{cases}$$

In the case of a finite buffer (space for $K - 1$ waiting packets, K packets in the system), define the tailprobability $P_k^{(t)} = \sum_{j=k}^{\infty} P_j = 1 - \sum_{j=-1}^{k-1} P_j$

In the case the transition matrix becomes

$$\mathbf{P} = \begin{pmatrix} P_0 + P_{-1} & P_{-1} & 0 & \cdots & 0 \\ P_1 & P_0 & P_{-1} & \cdots & 0 \\ P_2 & P_1 & P_0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ P_{K-1} & P_{K-2} & P_{K-3} & \cdots & P_{-1} \\ P_K^{(t)} & P_{K-1}^{(t)} & P_{K-2}^{(t)} & \cdots & P_0^{(t)} \end{pmatrix}$$

and $\boldsymbol{\pi} = [\pi_0 \; \pi_1 \cdots \; \pi_K]^T$.

Concentrate on case of infinite buffer, define the generating function

$$\begin{aligned} \pi(z) &= \sum_{k=0}^{\infty} \pi_k z^k \\ &= P_{-1}\pi_0 + \sum_{k=0}^{\infty}\sum_{r=0}^{k} \pi_r P_{k-r} z^k + P_{-1}\sum_{k=1}^{\infty} z^{k-1}\pi_k \end{aligned}$$

Let $i = k - r$, rewrite the previous equation

$$\begin{aligned} \pi(z) &= P_{-1}\pi_0 + \sum_{r=0}^{\infty}\sum_{i=0}^{\infty} \pi_r P_i z^{r+i} \\ &+ P_{-1}\left(\sum_{k=0}^{\infty} z^{k-1} - \frac{\pi_0}{z}\right) \\ &= P_{-1}\pi_0 + \left(\sum_{r=0}^{\infty} \pi_r z^r\right)\left(\sum_{i=0}^{\infty} P_i z^i\right) \\ &+ P_{-1}\frac{\pi(z)}{z} - \frac{P_{-1}\pi_0}{z} \end{aligned} \tag{4.5}$$

Define $P(z) = \sum_{i=0}^{\infty} P_i z^i$, so (4.5) can be written as:

$$\pi(z) = P_{-1}\pi_0 - \frac{P_{-1}\pi_0}{z} + \pi(z)P(z) + P_{-1}\frac{\pi(z)}{z}$$

so,

$$\pi(z) = \frac{P_{-1}\pi_0(z-1)}{z - P_{-1} - zP(z)} = \frac{P_{-1}\pi_0(1-z)}{\mathbb{P}(z) - z}$$

where $\mathbb{P}(z) \triangleq \sum_{i=-1}^{\infty} P_i z^{i+1} = P_{-1} + zP(z)$. Let $z = 1$, we can get,

$$\pi(1) = \sum_{i=0}^{\infty} \pi_i = 1 \tag{4.6}$$

and

$$\pi(1) = \lim_{z \to 1} \frac{P_{-1}\pi_0(1-z)}{\mathbb{P}(z) - z} = \frac{-P_{-1}\pi_0}{\mathbb{P}'(1) - 1} \tag{4.7}$$

where $\mathbb{P}'(z) = \sum_{i=-1}^{\infty}(i+1)P_i z^i$ and $\mathbb{P}'(1) = \sum_{i=-1}^{\infty}(i+1)P_i = 1 + \sum_{i=-1}^{\infty} iP_i = 1 - \mu$, with $\mu = -\sum_{i=-1}^{\infty} iP_i$.

Following the definition of μ, we observe: common sense indicates that the system with infinite buffer has a stationary distribution if and only if $\mu > 0$. In fact, the buffer content process is positive recurrent if $\mu > 0$, null recurrent if $\mu = 0$, and transient if $\mu < 0$.

Using the fact $P_{ST} + P_{FT} = 1$,

$$\begin{aligned} \mu &= e^{-\alpha}P_{ST} - \sum_{i=0}^{\infty} i\left[\frac{\alpha^i}{i!}e^{-\alpha}P_{FT} + \frac{\alpha^{i+1}}{(i+1)!}e^{-\alpha}P_{ST}\right] \\ &= e^{-\alpha}P_{ST} - e^{-\alpha}\left[\sum_{i=0}^{\infty} i\frac{\alpha^i}{i!} - P_{ST}\sum_{k=1}^{\infty}\frac{\alpha^k}{k!}\right] \end{aligned}$$

Note that

$$\sum_{i=1}^{\infty}\frac{\alpha^i}{i!} = e^{\alpha} - 1, \quad \sum_{i=0}^{\infty} i\frac{\alpha^i}{i!} = \alpha\sum_{i=0}^{\infty} i\frac{\alpha^{i-1}}{i!} = \alpha e^{\alpha}$$

So, the expression of μ can be gotten

$$\mu = P_{ST} - \alpha$$

The condition that $\mu > 0$ therefore is that $P_{ST} > \alpha$, which is “intuitively obvious”. (When there are packets waiting, the probability of success must be greater than the average number of new arrivals).

In the case of an infinite buffer, (4.6) and (4.7) show that

$$\pi_0 = \frac{\mu}{P_{-1}}$$

which confirms that the system needs $\mu > 0$, and then

$$\pi_1 = \frac{(1 - P_0 - P_{-1})\pi_0}{P_{-1}}$$

$$\pi_{k+1} = \frac{\pi_k - \sum_{r=0}^{k} \pi_r P_{k-r}}{P_{-1}}, \quad k \geq 1 \tag{4.8}$$

The method above works only in the case of an infinite buffer. If the buffer is finite, say has space for only K packets, the system is always stationary, whether $\mu > 0, \mu = 0$ or $\mu < 0$. In this case the stationarity distribution can be found as follows:

Choose $\pi_0 > 0$, further arbitrary, say $\pi_0 = 1$. Compute $\pi_1, \pi_2, \ldots, \pi_k$ iteratively from the last two formulas in (4.8). Then renormalize to get the sum of the probabilities $\pi_0 + \pi_1 + \cdots + \pi_K = 1$.

4.2.2 Throughput and Delay Analysis

In case of an infinite buffer the results in subsection A above lead to closed form results for throughput and delay. Define the throughput as the average number of the successfully transmitted data packets per period,

$$\begin{aligned} R &= \sum_{i=1}^{\infty} \pi_i \cdot P_{ST} + \pi_0 \left(1 - \frac{\alpha^0}{0!} e^{-\alpha}\right) P_{ST} \\ &= P_{ST}(1-\pi_0) - \pi_0 \frac{\alpha^0}{0!} e^{-\alpha} P_{ST} \\ &= P_{ST}\left(1 - \pi_0 e^{-\alpha}\right) \end{aligned} \tag{4.9}$$

The average packet delay equals the average of waiting time of each packet. The probability of the buffer is empty is π_0.

$$\pi'(z) = \sum_{i=1}^{\infty} i\,\pi_i\,z^{i-1}$$

The average number of packets in system is

$$L_s = \sum_{i=1}^{\infty} i\,\pi_i = z\,\pi'(z)|_{z=1}$$

Consider

$$\begin{aligned} z\pi'(z)|_{z=1} &= P_{-1}\pi_0 \frac{z + (z^2 - z)\mathbb{P}'(z) - z\mathbb{P}(z)}{(\mathbb{P}(z) - z)^2}|_{z=1} \\ &= P_{-1}\pi_0 \frac{\mathbb{P}''(1)}{2(\mathbb{P}'(1) - 1)^2} \end{aligned} \tag{4.10}$$

where

$$\mathbb{P}''(1) = \sum_{i=-1}^{\infty} i^2 P_i + \sum_{i=-1}^{\infty} i P_i \tag{4.11}$$

the second part of (4.11) is

$$\sum_{i=-1}^{\infty} i\,P_i = -\mu = \alpha - P_{ST}$$

and the first part is

$$\begin{aligned}\sum_{i=-1}^{\infty} i^2 P_i &= e^{-\alpha} P_{ST} + e^{-\alpha}\left[\sum_{i=0}^{\infty} i^2 \frac{\alpha^i}{i!}(1-P_{ST}) + P_{ST}\sum_{i=0}^{\infty} i^2 \frac{\alpha^{i+1}}{(i+1)!}\right] \\ &= e^{-\alpha} P_{ST} + e^{-\alpha}\left\{\sum_{i=0}^{\infty} i^2 \frac{\alpha^i}{i!} - P_{ST}\left[\sum_{i=0}^{\infty} i^2 \frac{\alpha^i}{i!} - \sum_{i=0}^{\infty} i^2 \frac{\alpha^{i+1}}{(i+1)!}\right]\right\} \\ &= e^{-\alpha} P_{ST} + e^{-\alpha}\left[\sum_{i=0}^{\infty} i^2 \frac{\alpha^i}{i!} - 2P_{ST}\sum_{i=0}^{\infty} i \frac{\alpha^i}{i!} + P_{ST}\sum_{i=1}^{\infty} \frac{\alpha^i}{i!}\right] \end{aligned} \tag{4.12}$$

Note that

$$\sum_{i=0}^{\infty} i^2 \frac{\alpha^i}{i!} = e^{\alpha}\left(\alpha^2 + \alpha\right)$$

So, we can find that

$$\mathbb{P}''(1) = \alpha^2 + 2(1-P_{ST})\alpha$$

The average number of packets in buffer is

$$L_q = L_s - (1-\pi_0)$$

and the average delay time of each packet is

$$T_q = \frac{L_q}{\lambda} \tag{4.13}$$

4.2.3 System Stability Analysis

In a skip free negative process, the condition that the system is stable is the probability that the state transfers from right to left equals to the probability that the state transfers from left to right, using global balance equation

$$\pi_k P_{k,k-1} = \sum_{j=0}^{k-1} \pi_j \sum_{l=k-j}^{\infty} P_{j,l} \tag{4.14}$$

it can be rewritten as:

$$\pi_k = \frac{1}{P_{k,k-1}} \sum_{j=0}^{k-1} \pi_j \sum_{l=k-j}^{\infty} P_{j,l}$$

Rewritten the previous equation, get

$$\pi_k = \sum_{j=k-n}^{k-1} \pi_j D_{n-j} = \sum_{j=1}^{n} D_j \pi_{k-j} \tag{4.15}$$

Let

$$\pi_j = Cx^j$$

and one can get

$$Cx^k = \sum_{j=1}^{n} D_j C x^{k-j}$$

divided by Cx^k at both sides of the previous equation,

$$1 = \sum_{j=1}^{n} D_j x^{-j} \tag{4.16}$$

Find the n solutions of equation 4.16 $x_1, x_2, \ldots, x_n$, then find $C_1, C_2, \ldots, C_n$, and the stationary probabilities are

$$\pi_k = C_1 x_1^{-k} + C_2 x_2^{-k} + \cdots + C_n x_n^{-k} \quad k = 0, 1, 2, \ldots, n-1$$

Since $0 \leq \pi_k \leq 1$, $|x_k| > 1$, that is the Markov chain is recurrent and the system is stable.

In another way, using the detailed balance equation for state k

$$P_{-1}\pi_{k+1} = \pi_k - \sum_{j=1}^{k} P_j \pi_{k-j}$$

and the probability of state $k+1$ is

$$\pi_{k+1} = \frac{\pi_k}{P_{-1}} - \frac{1}{P_{-1}} \sum_{j=1}^{k} P_j \pi_{k-j} \tag{4.17}$$

In the unlimited buffer size situation,

$$\mu = -\sum_{j=-1}^{\infty} jP_j = P_{-1} - \sum_{j=1}^{\infty} jP_j$$

From the definition of μ, common sense indicates that the system with infinite buffer has a stationary distribution if and only if $\mu > 0$. In fact, the buffer content process is positive recurrent if $\mu > 0$, null recurrent if $\mu = 0$, and transient if $\mu < 0$.

From 4.17, similar to equation 4.15,

$$\pi_{k+1} = D_k\pi_k - \sum_{j=0}^{k} D_j\pi_{k-j}$$

Let $\pi_k = Cx^k$ and rewrite it

$$Cx^{k+1} = CD_kx^k - \sum_{j=1}^{k} D_jCx^{-j}$$

$$1 = D_kx^{-1} - \sum_{j=1}^{n} D_jCx^{k-j}$$

Find the n solutions of equation 4.16 $x_1, x_2, \ldots, x_n$, then find $C_1, C_2, \ldots, C_n$, and the stationary probabilities are

$$\pi_{k+1} = C_1x_1^{-k} - C_2x_2^{-k} - \cdots - C_nx_n^{-k} \quad k = 0, 1, 2, \ldots, n-1$$

$$P_{-1}\pi_{k+1} = \pi_k - \sum_{j=1}^{k} P_j\pi_{k-j}$$

so,

$$P_{-1} = x - \sum_{j=1}^{n} P_jx^j$$

It is impossible to find $0 \leq |x_k| \leq \infty$ making $0 \leq \pi_k \leq 1$, the markov chain is transit and the system is unstable.

4.2.4 Drop Probability and Go Through Delay Analysis

In case of a finite buffer size [25], the new arrival will be dropped when the buffer is full. The probability of packet be dropped is

$$\begin{aligned} P_{drop} &= \pi_K \, (P_0^{(t)} - P_0) + \pi_{K-1} \, (P_1^{(t)} - P_1) + \cdots \\ &+ \pi_0 \, (P_K^{(t)} - P_K) \\ &= \sum_{i=0}^{K} \pi_i \left(P_{K-i}^{(t)} - P_{K-i} \right) \end{aligned} \tag{4.18}$$

Moreover, define delay as the delay of the packets that actually get through. The average number of packets in system is

$$L_s = \sum_{i=0}^{K} i\pi_i$$

The average number of packets in buffer is

$$L_q = L_s - (1 - \pi_0)$$

and the average go through delay of each packet is

$$T_q = \frac{L_q}{\lambda(1 - P_{drop})}$$

If the buffer size increases, the fraction of customers that get dropped decreases and the average go through delay increase. If $\mu > 0$, buffer size gets large (to infinite), drop probability goes to zero, while average delay goes to some constant. If $\mu < 0$, buffer gets large, drop probability goes to $1 - \frac{P_{ST}}{\alpha}$ and delay goes to infinite, as fast as $\frac{K}{P_{ST}}$. If $\mu = 0$, buffer gets large, drop probability goes to zero, and delay goes to infinite, as fast as $\frac{1}{2}\frac{K}{P_{ST}}$.

4.3 Performance Analysis Using M/G/1 Queueing Model

Consider a queueing system immediately after a customer has departed and service is about to commence on the next customer in queue, with service times assumed to be independently and identically distributed random variables with an arbitrary probability distribution. Denote the service time by b, and the cumulative distribution function by $B(t)$. The arrival process is Poisson with parameter λ. The imbedded stochastic process $X(t_i)$, where X denotes the number of customs in the system and t_i is the completion time of the ith customer, can be shown to be Markovian as follows [45].

$$Pr\{X_{n+1} = j | X_n = i\} = \begin{cases} \int_0^{\infty} \frac{e^{-\lambda t}(\lambda t)^{j-i+1}}{(j-i+1)!} dB(t) & (j \geq i-1, i \geq 1), \\ 0 & (j < i-1, i \geq 1). \end{cases} \quad (4.19)$$

4.3.1 Delay Performance Analysis

The performance of such a system is analyzed from the network aspect. In considering the packet passing through the network via the virtual bit pipe from the source to the sink. Consider a queueing system where packets arrive at random times for service. Define the transmission period for one packet as τ. The traffic load follows the Poisson distribution with rate λ,

A given packet transmitted might be retransmit due to errors (see Figure 4.2) . It follows that the time interval between the start of the first transmission and the last transmission of a given packet is $k\tau$ with probability $P_{ST}P_{FT}^{k-1}$. The transmitter queue behaves like an M/G/1 queue with service time distribution given by

$$P\{b = k\tau\} = P_{ST}P_{FT}^{k-1} = (1-P)P^{k-1}, \quad k = 1, 2, \ldots$$

where $P \triangleq P_{FT} = 1 - P_{ST}$ is the probability of the packet transmission failure, $P_{ST} = (1 - P_e)^{Len}$ is the successful transmission probability , Len is the length of the packet and P_e is the bit error rate.

The first two moments of the service time are

$$\bar{b} = \sum_{k=0}^{\infty} k\tau(1-P)P^{k-1} = \tau(1-P)\sum_{k=0}^{\infty} kP^{k-1}$$

$$\overline{b^2} = \sum_{k=0}^{\infty} k^2\tau^2(1-P)P^{k-1} = \tau^2(1-P)\sum_{k=0}^{\infty} k^2P^{k-1}$$

Note that

$$\sum_{k=0}^{\infty} kP^{k-1} = \frac{1}{(1-P)^2}$$

and

$$\sum_{k=0}^{\infty} k^2P^{k-1} = \frac{1+P}{(1-P)^3}$$

(The sums are obtained by differential $\sum_{k=0}^{\infty} P^k = \frac{1}{1-P}$). Using these formulas in the equation for $\bar{b}$ and $\overline{b^2}$ above, one can obtain

$$\bar{b} = \tau(1-P)\frac{1}{(1-P)^2} = \frac{\tau}{1-P}$$

$$\overline{b^2} = \tau^2(1-P)\frac{1+P}{(1-P)^3} = \tau^2\frac{1+P}{(1-P)^2}$$

The P-K formula gives the average packet time in queue

$$W = \frac{\lambda\overline{b^2}}{2(1-\lambda\bar{b})} \tag{4.20}$$

We observe that, the average service time is constant (depends on P), the average waiting time increase while the packets arrival rate increase, when the packet arrival rate increase close to the service rate, the average waiting time goes to infinity. So, the system is stable when $(1-\lambda\bar{b}) > 0$, that is $\lambda < \frac{1}{\bar{b}}$ (the packet arrival rate is less than the average service rate). The average delay time of each packet is

$$T = \bar{b} + W \tag{4.21}$$

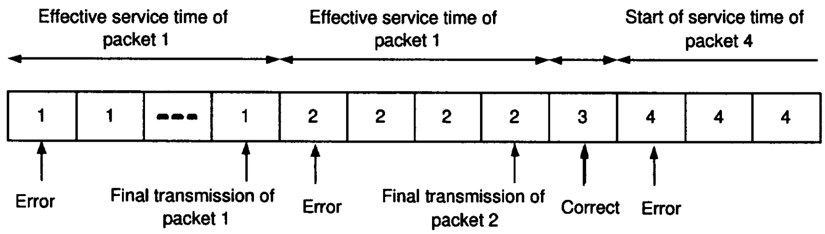

Figure 4.2 Illustraction of the effective service time of packet in the system. For example, packet 1 has an effective service time of 4 because there were 3 errors in the first three times attempt to transmit it, but no error in the forth attempt.

4.3.2 Departure-Point Steady-State System-Size Probability

Let π_n represent the probability of n in the system at a departure point (a point of time just slightly after a customer has completed service) after steady state is reached. The imbedded stochastic process at departure points is a Markov chain. Denote the transition probability matrix by

$$\mathbf{P} = \{p_{ij}\}$$

where

$$\begin{aligned} p_{ij} &= Pr\{\text{system size immediately after a departure point is } j| \\ &\quad \text{system size after previous departure was } i\} \\ &= Pr\{X_{n+1} = j | X_n = i\} \end{aligned} \tag{4.22}$$

Simplification results on defining

$$k_n = Pr\{n \text{arrivals during a service time}\} = \int_0^\infty \frac{e^{-\lambda t}(\lambda t)^n}{(n)!} dB(t)$$

so that p_{ij} can be seen to equal k_{j-i+1} and

$$\mathbf{P} = \{p_{ij}\} = \begin{pmatrix} k_0 & k_0 & 0 & 0 & 0 & \cdots \\ k_1 & k_1 & k_0 & 0 & 0 & \cdots \\ k_2 & k_1 & k_0 & k_0 & 0 & \cdots \\ k_3 & k_3 & k_2 & k_1 & k_0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & & \vdots\ddots \end{pmatrix} \tag{4.23}$$

Assume steady state is achievable, the steady-state probability vector $\boldsymbol{\pi} = \{\pi_n\}$, can be found as the solution to the stationary equation

$$\boldsymbol{\pi}^T\mathbf{P} = \boldsymbol{\pi}^T$$

This yields

$$\pi_i = \pi_0\, k_i + \sum_{j=1}^{i+1} \pi_j\, k_{i-j+1} \quad (i = 1, 2, \ldots) \tag{4.24}$$

Now define the generating functions

$$\Pi(z) = \sum_{i=0}^{\infty} \pi_i z^i \quad \text{and} \quad K(z) = \sum_{i=0}^{\infty} k_i z^i \quad (|z| < 1)$$

Then multiplying (4.24) by z^i, summing over i, and solving for $\Pi(z)$

$$\Pi(z) = \frac{\pi_0(1-z)K(z)}{K(z)-z}$$

Using the fact $\Pi(1) = 1$, along with L'Hôpital's rule, and realizing that $K(1) = 1$ and $K'(1) = \frac{\lambda}{\mu}$

$$\pi_0 = 1 - \rho \quad (\rho \equiv \lambda E[\text{service time}])$$

Hence

$$\Pi(z) = \frac{(1-\rho)(1-z)K(z)}{K(z)-z} \tag{4.25}$$

Define the throughput as the average number of the successfully transmitted data packets per period,

$$\begin{aligned} R &= \sum_{i=1}^{\infty} \pi_i \cdot P_{ST} \\ &= P_{ST}(1-\pi_0) \end{aligned} \tag{4.26}$$

4.3.3 Finite M/G/1 Queues

In this section, the finite buffer size is studied. The M/G/1 queueing system with finite-capacity is denoted by M/G/1/K system, where K is the capacity of a system such that $1 \leq K \leq \infty$, as shown in Figure 4.3. Two major performance measures in the M/G/1/K system are the go through delay D (mean response time [46]) of a message that is accepted in the system, and the drop probability P_d (blocking probability) that an arrival message is droped/blocked because the system is full when it arrivals. The throughput R of the system, that is, the mean number of messages that actually served per unit time, is

$$R = \lambda(1 - P_d)$$

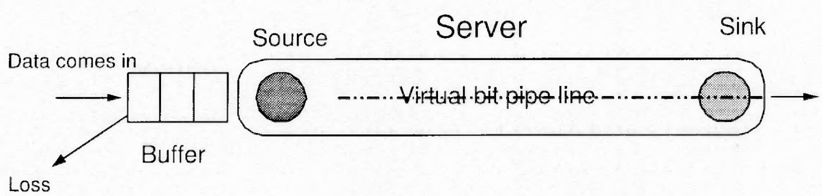

Figure 4.3 An M/G/1/K queueing system.

Define $\rho = \lambda b$ as the traffic load (offered load) of the system, where $\bar{b}$ is mean for the service time of a message. The carried load of the system is $\rho' = \gamma\bar{b} = \rho(1 - P_d)$, which is the fraction of the time that the service is busy. From Little's theorem applied to those message accepted in the system,

$$L = \gamma D \tag{4.27}$$

The analysis of the finite-capacity M/G/1/K queue proceeds in a similar way to that of the infinite buffer size case. The PK formulas will not hold because the expected number of arrival during a service period must be conditioned on the system size. The single-step transition matrix must here be truncated at $K-1$, so that,

$$\mathbf{P} = \{p_{ij}\} = \begin{pmatrix} k_0 & k_0 & 0 & 0 & \cdots & 0 \\ k_1 & k_1 & k_0 & 0 & \cdots & 0 \\ k_2 & k_2 & k_1 & k_0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & & \vdots \\ 1-\sum_{n=0}^{K-2} k_n & 1-\sum_{n=0}^{K-2} k_n & 1-\sum_{n=0}^{K-3} k_n & 1-\sum_{n=0}^{K-4} k_n & \cdots & 1-k_0 \end{pmatrix} \tag{4.28}$$

implies that the stationary equation is

$$\pi_{i+1} = \begin{cases} \pi_0\, k_i + \sum_{j=1}^{i} \pi_j\, k_{i-j+1} & i = 1, 2, \ldots, K-2 \\ 1 - \sum_{j=0}^{K-2} \pi_j & i = K-1 \end{cases} \tag{4.29}$$

Equation 4.29 provide K independent equations for K unknowns (π_k $0 \le k \le K-1$).

An efficient algorithm for computing π_k can be given in terms of [47]

$$\pi'_k \triangleq \frac{\pi_k}{\pi_0} \quad 0 \le k \le K \tag{4.30}$$

It is easy to see form 4.29 that $\{\pi'_k; 0 \leq k \leq K-1\}$ can be recursively calculated as follows:

$$\pi'_0 = 1 \tag{4.31}$$

$$\pi'_{k+1} = \frac{1}{k_0}\left(\pi'_k - \sum_{j=1}^{k} \pi'_j k_{k-j+1} - k_k\right) \quad 0 \leq k \leq K-1 \tag{4.32}$$

and π_0 is found from $\sum_{k=0}^{K-1} \pi_k = 1$ as

$$\pi_0 = \left(\sum_{k=0}^{K-1} \pi'_k\right)^{-1}$$

Thus we get π_k from 4.30. The computational complexity of this algorithm is of order $O(k^2)$. Note that the above form for the set of linear equations for π'_k is called an *upper Hessenberg matrix*, and is suitable for numerical computation [48]. Furthermore, it is note that the probability distribution for the system size encountered by an arrival will be different form $\pi_k, 0 \leq k \leq K$. Let q'_k then denote the probability that an arrival message (whether is joins the queue or not) finds k message in the system, and let $P_k, (k = 0, 1, 2, \ldots, K)$ be the probability that there are k packets presents in the system at an arbitrary time. From the theorem that Poisson arrivals see time averages (PASTA) [49],

$$q'_k = P_k \quad 0 \leq k \leq K$$

and

$$q'_k = (1 - P_d)\pi_k \quad 0 \leq k \leq K$$

Compare the previous two equations,

$$P_k = c\pi_k$$

where c is a proportional constant.

We also have that

$$\sum_{k=0}^{K} P_k = 1$$

.

Note that

$$\begin{aligned} P_0 &= 1 - \rho' \\ P_d &= q'_K = P_K \end{aligned} \tag{4.33}$$

Obtain the relation $P_K = 1 - \frac{1-P_0}{\rho}$ and $c = \frac{1}{\pi_0 + \rho}$.

Thus, the probability of k packet in the system is

$$\begin{aligned} P_k &= \frac{\pi_k}{\pi_0 + \rho} \\ P_K &= 1 - \frac{1}{\pi_0 + \rho} = P_d \end{aligned} \tag{4.34}$$

The mean of the number of packets in the system at an arbitrary time is thus given by

$$L = \sum_{i=0}^{K} iP_i = \frac{\sum_{k=1}^{K-1} k\pi_k}{\pi_0 + \rho} + K(1 - \frac{1}{\pi_0 + \rho}) \tag{4.35}$$

.

From 4.27, the go through delay is

$$D = \frac{1}{\lambda}\left[\sum_{k=1}^{K-1} k\pi_k + K(\pi_0 + \rho - 1)\right]$$

CHAPTER 5

EXTENDING LIFETIME OF THE NETWORK AND CRUCIAL NODE BY MULTIPLE DIVERSITY COMBINING

5.1 Motivation

The cross-layer design in wireless sensor networks has received much attention among researchers both in physical layer and network layer. The cross-layer design facilitates efficient and collaborative utilization of network resources in protocol based communication systems. Traditionally, in wired networks, the MAC layer is designed using a simple collision avoidance model. Most of the conventional random access protocols assume that the failure of reception is caused by collisions and the channel is noiseless. Therefore, collided packets are destroyed and retransmission must be made later. Simple random access protocols of ALOHA type 'resolve' collisions by randomizing retransmission to improve system performance [44]. Carrier sensing multiple access (CSMA) and collision detection mechanism are also employed to improve the throughput performance by collision detection in wired networks. The emphases in the random access mechanisms have been mostly on retransmission schemes that minimizing future collisions [6]. However, the collided packets are typically discarded when a collision does occur, and no information is exploited from them. In cellular data networks, data sensing multiple access (DSMA) is usually implemented. The base station detects collisions and continuously broadcasts a busy/idle signal through a control channel to all users. In a wireless network, users share a common *unreliable* wireless channel due to fading, interference and background noise. The receiver at a given node is designed to extract from data the signals of interested users. Better approaches to resolving and separating collisions improve the throughput and performance of the system. The key to successful signal separation is the transmission and/or receiving *diversity* embedded in the received data packages. Diversity can be introduced both at the transmitter and at the receiver. The transmit diversity introduces redundance into the transmitted data package using modulation, coding, and spreading techniques. The spatial diversity is another technique for reliable signal reception and separation [50]. The use of antenna arrays provides additional degrees of freedom in multi-packet reception and separation [51]. The framework of multiuser detection [52] is the essence of many signal separation methods. The transmit diversity, receiver diversity, and multiuser detection are mainly implemented in physical layer. In addition, recent research also uses network resources to provide diversity through selective retransmission [53].

The goal of this chapter is to combine the diversities provided by different protocol layers for multi-packet reception in random access wireless networks. In this approach, employing antenna arrays at collector allows the separation of multiple transmitting at the same time when the number of active sensor nodes is less than the number of the antennas. However, with the increase of the active nodes, the collector can not extract the data by the space diversity only. Then the received packets that have collided are stored in memory. They are later combined with future retransmission in order to extract all the collided information.

5.2 Crucial Nodes

In wireless sensor network, the sensor nodes are usually scattered in a sensor field as shown in Figure 5.1. These nodes collect data and route data to the collector, the collector communicates with the process center.

In non-mission-critical application, the definition of lifetime is the cumulative active time of the network (i.e. whenever the network is active its lifetime clock is ticking, otherwise not.) In mission-critical applications, lifetime is defined as the cumulative active time of network until the first loss of coverage or quality failure [54]. In this dissertation the network lifetime is defined as the time interval between the time that sensor network starts its operation and the time that the collector losses communication with all sensor nodes. In most cases, when all the nodes that can communicate with the collector directly expire, the sensor network is completely 'dead'. Therefore, these nodes with one hop away from the collector are called crucial nodes because their lifetime are more important than other nodes for the network lifetime.

Assume that a sensor network consists of a total of N_{total} randomly deployed nodes. Denote the sensor node set $\mathcal{S} = \{s_1, s_2, \cdots, s_{Ntotal}\}$, $|\mathcal{S}| = N_{total}$, where $|\cdot|$ is the cardinal number of a set [26]. Define $\mathcal{C} = \{s_i | r_i < d_{max}, s_i \in \mathcal{S}\}$, $|\mathcal{C}| = J$ where r_i is the distance between node s_i and the collector, and d_{max} is the maximum transmission range of a node, as the set of crucial sensors and the collector can only receive the packets from/through one node in this set. Therefore, the lifetime of the whole network is determined by the lifetime of set $\mathcal{C}$ which depends on the traffic generated and relayed by these nodes. In order to extend the network lifetime, we try to minimize the average energy consumption at these crucial nodes.

To achieve the goal of energy efficiency, it is necessary to identify the main sources that waste energy. The major sources of energy waste in sensor networks are: collision, overhearing, control packet overhead and idle listening. Due to the high traffic load at these crucial nodes, collision is the primary energy waste source and increases the latency as well.

5.3 System Model

Let us consider a wireless sensor network with K active transmitting nodes, each using a slotted random access scheme [27]. Specially, node k transmits a length-N data packet, $\mathbf{d}_k(n) = \begin{bmatrix} d_{k,1}(n), & \cdots, & d_{k,N}(n) \end{bmatrix}^T$, during the n-th time slot. Assume that the collector (receiving node) uses an antenna array of M sensors. Within the n-th time slot,

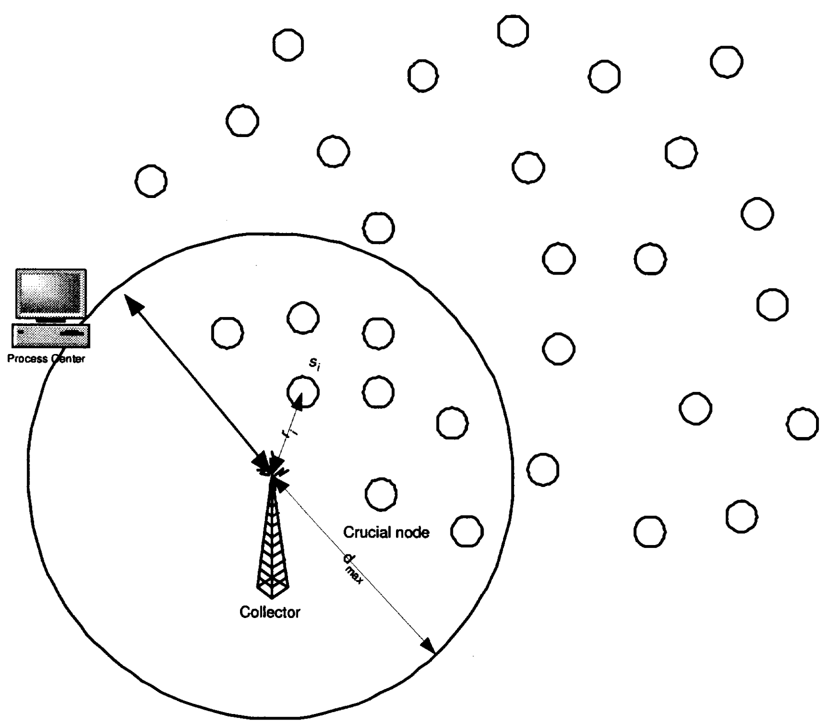

Figure 5.1 Crucial nodes in a multi-hop sensor networks.

the data vector received by the m-th antenna can be modeled as,

$$\mathbf{y}_m(n) = \sum_{k=1}^{K} a_{k,m}(n)\mathbf{d}_k(n) + \mathbf{v}_m(n)\,, \tag{5.1}$$

where $a_{k,m}(n)$ denotes the channel gain (a real-valued Gaussian random variable) between the k-th transmitter (node) and the m-th antenna, vector $\mathbf{v}_m(n)$ is the real-valued addictive white Gaussian noise at the m-th antenna.

The total received data from all M antennas within the n-th time slot, collected in a $N \times M$ matrix, can be modelled as

$$\begin{aligned} \mathbf{Y}(n) &= \begin{bmatrix} \mathbf{y}_1(n), & \cdots, & \mathbf{y}_M(n) \end{bmatrix} \\ &= \sum_{k=1}^{K} \mathbf{d}_k(n)\,\mathbf{a}_k^T(n) + \mathbf{V}(n) \qquad (5.2) \\ &= \mathbf{D}(n)\,\mathbf{A}(n) + \mathbf{V}(n)\,, \end{aligned}$$

where $\mathbf{A}(n)$ is a $K \times M$ mixing matrix with $\mathbf{a}_k^T(n) = \begin{bmatrix} a_{k,1}(n), & \cdots, & a_{k,M}(n) \end{bmatrix}, k = 1, 2, \ldots, K$ as its rows; the $N \times K$ matrix $\mathbf{D}(n) = \begin{bmatrix} \mathbf{d}_1(n) & \cdots & \mathbf{d}_K(n) \end{bmatrix}$ contains K collided packages; $\mathbf{V}(n) = \begin{bmatrix} \mathbf{v}_1(n) & \cdots & \mathbf{v}_M(n) \end{bmatrix}$ is the noise matrix.

In a simple network using random access protocols, when a collision is detected, the received packets $\mathbf{Y}(n)$ are discarded and the system initiates a retransmission schedule. However, from (5.2) we know that the data matrix $\mathbf{Y}(n)$ contains information of all collided packets, hence, it should be exploited with the help of additional data transmission for collision resolution. We notice the fact that the reception diversity from the M-element receiving antenna array provides M copies of the transmitted packages $\mathbf{D}(n)$, each being scaled by a different channel gain vector (the m-th column of matrix $\mathbf{A}(n)$). Hence, we can resolve K transmission nodes' packages as long as $M \geq K$. Based on this observation, it is possible to propose a *collaborative approach* to combining the spatial diversity with the network assisted diversity to separate and extract information from received data packages in collision.

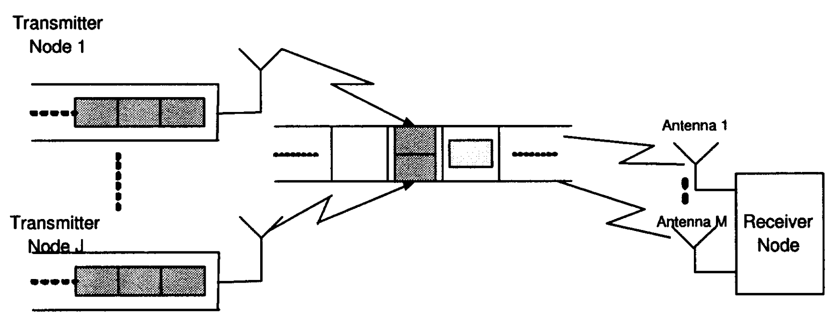

Figure 5.2 A random access, slotted wireless system with receiving antennas.

5.4 Collision Resolution through Signal Separation

5.4.1 Network Assisted Diversity Multiple Access

In principle, collision resolution is equivalent to signal separation. The network assisted diversity multiple access (NDMA) approach can be used for this purpose [53].

Let us consider the case when K transmission nodes collide in a given time slot n. The receiver has only one receive antenna. Therefore the received data vector $\mathbf{y}(n)$ consists of a mixture of K packages from different sources. That is,

$$\mathbf{y}_{NA}(n) = \sum_{k=1}^{K} a_k(n)\,\mathbf{d}_k(n) + \mathbf{v}(n) \ = \mathbf{D}(n)\,\mathbf{a}(n) + \mathbf{v}(n)\,,$$

where the information $\mathbf{D}(n) = \begin{bmatrix} \mathbf{d}_1(n) & \cdots & \mathbf{d}_K(n) \end{bmatrix}$, and $\mathbf{a}(n) = \begin{bmatrix} a_1(n), & \cdots, & a_K(n) \end{bmatrix}^T$. Apparently, at least an additional $(K-1)$ snapshots of $N \times 1$ data vector are needed to resolve the $N \times K$ information matrix $\mathbf{D}(n)$. From a signal processing perspective, this problem may be solved if there is a method to create a Γ branch diversity with $\Gamma \geq K$ and collect Γ independent mixtures of the signals $\mathbf{d}_k(n)$. With the network layer knowledge, all transmission nodes are aware of the fact that a collision with multiplicity K occurred during the time slot n. Therefore, each of the K nodes will retransmit its packets $K-1$ more times in the next $K-1$ time slots. No other node will initiate a new transmission during these $K-1$ slots. With this collision detection and retransmission protocol, the receiver will receive a total K copies of the collided packets,

$$\mathbf{Y}_{NA}(n) = \mathbf{D}(n)\,\mathbf{A}(n) + \mathbf{V}(n)\,, \tag{5.3}$$

where $\mathbf{Y}_{NA}(n) = \begin{bmatrix} \mathbf{y}_{NA}(n) & \cdots & \mathbf{y}_{NA}(n+K-1) \end{bmatrix}$ is the $N \times K$ data mixing matrix, the $K \times K$ channel gain matrix is $\mathbf{A}(n) = \begin{bmatrix} \mathbf{a}(n) & \cdots & \mathbf{a}(n+K-1) \end{bmatrix}$, and the $N \times K$ noise matrix $\mathbf{V}(n) = \begin{bmatrix} \mathbf{v}(n) & \cdots & \mathbf{v}(n+K-1) \end{bmatrix}$.

If the mixing matrix $\mathbf{A}(n)$ of full rank is known or can be estimated, a simple linear inverse filtering solution can be used for data package separation,

$$\hat{\mathbf{D}}(n) = \mathbf{Y}_{NA}(n)\,\mathbf{A}^{-1}(n)\,. \tag{5.4}$$

Since only K time slots are required to construct a full rank mixing matrix $\mathbf{A}(n)$ for separating K collided packets, no slot is wasted and no throughput penalties incurred by the technique.

5.4.2 Space and Network Assisted Diversity Multiple Combining Access

Consider the similar case as in Section 5.4.1, but the receiver now is equipped with an array with M receiving antennas. Using the similar protocol, each of the K nodes will retransmit its information packet $L-1$ more times in the next $L-1$ slots (i.e. slots $n+1$, $\cdots$, $n+L-1$). An example of this protocol for a collision of 3 nodes and 2 receive antennas is shown in the Figure 5.3.

$$L = \lceil \frac{K}{M} \rceil \tag{5.5}$$

No other nodes will transmit a new packet in the next $L-1$ slots. Assume that no other nodes will transmit a new packet in the next $L-1$ slots. The proposed approach can resolve the packet collision during L time slots. Thus it is M times faster than NDMA to resolve colliding packets. The assumption holds when other nodes are notified by using a busy tone signal as stated in subsection 5.4.3. Only the colliding nodes will retransmit their packets in the next $L-1$ slots according to the in-band busy signal while the other nodes will remain deferred within the $L-1$ slots. Considering that both NDMA and proposed approach assume that no other active users transmit packets during the resolution period, the new approach is able to provide more opportunities for other deferred nodes to access channels in the next time slots. Since they are less likely to enter the back off waiting stage, the proposed approach achieves higher throughput and fairness than NDMA. The receiver will receive a total $L \times M$ copies of the collided packets with these conventions.

$$\boldsymbol{\mathcal{Y}}(n) = \mathbf{D}(n)\,\boldsymbol{\mathcal{A}}(n) + \boldsymbol{\mathcal{V}}(n)\,, \tag{5.6}$$

where data $\mathcal{Y}(n)$ is $N \times (ML)$ matrix, the channel gain $\mathcal{A}(n)$ is $K \times (ML)$ matrix and noise $\mathcal{V}(n)$ is $N \times (ML)$ matrix,

$$\mathcal{Y}(n) = \begin{bmatrix} \mathbf{Y}(n) & \cdots & \mathbf{Y}(n+L-1) \end{bmatrix}$$

$$\mathcal{A}(n) = \begin{bmatrix} \mathbf{A}(n) & \cdots & \mathbf{A}(n+L-1) \end{bmatrix}$$

$$\mathcal{V}(n) = \begin{bmatrix} \mathbf{V}(n) & \cdots & \mathbf{V}(n+L-1) \end{bmatrix}$$

Equation (5.6) represents a classical source separation problem. If the mixing matrix $\mathcal{A}(n)$ is known or can be estimated, the maximum likelihood estimation of the transmitted packets is

$$\hat{\mathbf{D}}(n) = \arg\min_{\mathbf{D}} \| \mathcal{Y}(n) - \mathbf{D}\,\mathcal{A}(n) \|_F^2 \tag{5.7}$$

where $\|\cdot\|_F$ represents the Frobenius norm, and $\mathbf{D}$ takes all possible finite values. Since $ML \geq K$, the $rank\,(\mathcal{A}(n)) \geq K$. The ZF and MMSE solution for the desired data [55] can be gotten.

$$\hat{\mathbf{D}}_{ZF} = \mathcal{Y}(n)\mathcal{A}^H(n)(\mathcal{A}(n)\mathcal{A}^H(n))^{-1} \tag{5.8}$$

$$\hat{\mathbf{D}}_{MMSE} = \mathcal{Y}(n)\mathcal{A}^H(n)(\mathcal{A}(n)\mathcal{A}^H(n) + \sigma^2\mathbf{I})^{-1} \tag{5.9}$$

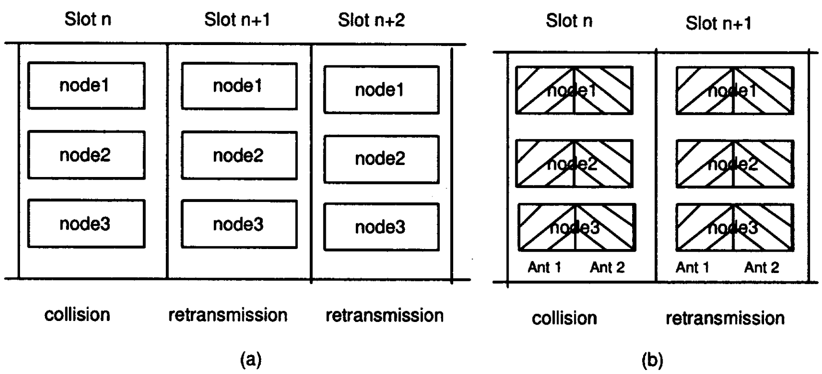

Figure 5.3 Packet collision and retransmission with 3 transmission nodes and 1 to 2 receiving antennas. With spatial diversity at reception, only 2 transmissions are required to resolve collision among 3 transmission nodes in (b).

5.4.3 The Signal Separation

Generally, a guard period is needed at the beginning of each slot in a slotted network [56]. Every node listens to the carrier during this guard period, and transmits its data after this period. One can use such a guard period to inform nodes of the collision with a busy signal. The receiver has to discriminate all the active transmitting nodes. There are 2^J different possibilities in a J-transmitting-node system. A unique ID sequence for each node contained in the packet is required in order to enable the receiver to uniquely identify all the active transmitting nodes. Assume that the first Q symbols of each packet of node k is the ID sequence, that is $\bar{\mathbf{d}}_k = [\mathbf{d}_k(n)]_{1:Q}$. The corresponding received data is,

$$\bar{\mathbf{y}}_m(n) = \sum_{k=1}^{K} a_{k,m}(n)\,\bar{\mathbf{d}}_k + \bar{\mathbf{v}}_m(n) \tag{5.10}$$

where $\bar{\mathbf{y}}_m(n) \triangleq [\mathbf{y}_m(n)]_{1:Q}$, and $\bar{\mathbf{v}}_m(n) \triangleq [\mathbf{v}_m(n)]_{1:Q}$. From (5.10), the estimation of $a_{k,m}(n)$ from the received data $\bar{\mathbf{y}}(n)$ is related to a least square (LS) problem. Assume that the ID sequences are orthogonal to each other.

$$\bar{\mathbf{d}}_k^T \bar{\mathbf{d}}_l = \{ \begin{array}{ll} 0 & k \neq l \\ 1 & k = l \end{array} .$$

the matched-filter output $z_{k,m}(n)$ associated with $\bar{\mathbf{d}}_k$ is

$$z_{k,m}(n) = \bar{\mathbf{d}}_k^T \bar{\mathbf{y}}_m(n) = a_{k,m}(n) + \bar{\mathbf{d}}_k^T \bar{\mathbf{v}}(n) , \tag{5.11}$$

Therefore vector $\mathbf{z}_m(n) = [z_{1,m}(n), \cdots, z_{K,m}(n)]^T$ forms the sufficient statistic for estimating the node gain $\mathbf{a}_m(n) = [a_{1,m}(n), \cdots, a_{K,m}(n)]^T$ for the mth antenna.

$$\hat{\mathbf{a}}_m(n) = \mathbf{z}_m(n) \tag{5.12}$$

5.5 Goodput and Delay Analysis

5.5.1 Goodput Analysis

It is instructive for us to view the traffic in the channel as a flow of collision resolution periods or epochs. An epoch includes one or several consecutive channel slots that are dedicated for the transmission (including the initial transmission and retransmissions) of the data packets from the nodes who are active at the beginning of the epoch. The idle slots, during which no data are transmitted, also compose epochs called idle epochs, which only include one slot. Correspondingly, we call those epochs, during which some packets are under transmission, busy epochs. The length of a busy epoch is the number of time slots the channel takes to serve the currently active transmission nodes.

The epoch length is a random variable depending on the number of the active transmission nodes at the beginning of the epoch. If denote by P_{emp} the probability of a transmission node's buffer being empty at the beginning of an epoch, then binomial expressions for probability of the length l epoch busy or idle can be obatained,

$$P_{busy}(k) = \binom{J}{k} (1 - P_{emp})^k \, P_{emp}^{J-k} \tag{5.13}$$

$$P_{idle}(k) = \begin{cases} P_{emp}^J & k = 1 \\ 0 & \text{otherwise} \end{cases} \tag{5.14}$$

where $k = 1, 2, \cdots, J$ is the number of active transmission nodes and J is the total number of transmission nodes in the network.

Let us define the goodput as

$$R = \frac{\text{average length of busy epoch} \cdot (1 - P_e)}{\text{average length of (busy or idle) epoch}}$$

We can obtain

$$R = \frac{\sum_{k=1}^{J} k \binom{J}{k} (1 - P_{emp})^k P_{emp}^{J-k} \cdot (1 - P_e(k))}{\sum_{k=1}^{J} k \binom{J}{k} (1 - P_{emp})^k P_{emp}^{J-k} + 1 \cdot P_{emp}^{J}} \tag{5.15}$$

where $P_e(k)$ is the bit error rate for active transmission node k.

5.5.2 Delay Analysis

From the viewpoint of a particular transmission node, two types of epochs (see Figure 5.4) can be distinguished: relevant epochs, in which a data packet belonging to this node is being transmitted, and irrelevant epochs, in which no packet belonging to this node is being transmitted. The lengths of two types of epochs, denoted by l_r and l_i, obey different distributions,

$$P_{l_r}(L) = \binom{K-1}{J-1} (1 - P_{emp})^{K-1} P_{emp}^{J-K}, \qquad 1 \leq K \leq J \tag{5.16}$$

$$P_{l_i}(L) = \begin{cases} P_{emp}^{J-1} + (J-1)(1 - P_{emp}) P_{emp}^{J-2}, & K = 1 \\ \binom{K}{J-1} (1 - P_{emp})^K P_{emp}^{J-K-1}, & 1 < K \leq J-1 \end{cases} \tag{5.17}$$

where $L = K$ in NDMA scheme, and for space and network combining approach L is chosen according to (5.5).

Denote q_m as the number of data packets in the buffer of a user at the beginning of the mth epoch. The sequence constitutes an Markov chain.

$$q_{m+1} = \begin{cases} q_m - 1 + v(q_m) & q_m > 0 \\ v(q_m) & q_m = 0 \end{cases} \tag{5.18}$$

where $v(q_m)$ be the number of data packets arriving during the mth epoch.

The probability generating function of q_m is

$$Q_m(z) = \sum_{k=0}^{\infty} Prq_m = kz^k = E[z^{qm}] \tag{5.19}$$

and the steady state of $Q_m(z)$ is $Q(z) = \lim_{m\to\infty} Q_m(z)$.

$$F(z) = \lim_{m\to\infty} E[z^{v(q_m}|q_m = 0]$$
$$G(Z) = \lim_{m\to\infty} E[z^{v(q_m}|q_m > 0]$$

If the buffer is fed by a Poisson source with rate λ, the steady-state probability generating function $Q(z)$ is

$$Q(z) = P_{emp}\frac{zF(z) - G(z)}{z - G(z)}$$

and

$$F(z) = \sum_{k=1}^{J} e^{k(z\lambda-\lambda)} P_{lr}$$
$$G(Z) = \sum_{k=1}^{J-1} e^{k(z\lambda-\lambda)} P_{li}$$

Let $z = 1$ in equation 5.19, we can find the relationship between P_{emp} and λ, P_{emp} is the unique solution in $[0, 1]$ of the equation

$$\lambda P_{emp}^{J} + (1 + \lambda J)P_{emp} - (1 - \lambda J) = 0 \tag{5.20}$$

A transmission node's buffer can also be modeled as an M/G/1 queue with vacation, in which the relevant epoch and irrelevant epoch play the role of the service time and vacation time respectively. According to the property of the M/G/1 queue with vacation, the average system delay (including the waiting time in the buffer and the transmission time in the channel) for a data packet can be expressed as

$$D = \bar{l}_r + \frac{\lambda \bar{l}_r^2}{2(1 - \lambda \bar{l}_r)} + \frac{\bar{l}_i^2}{2\bar{l}_i} \tag{5.21}$$

where packet arrival is a Poisson process with packet arrival rate λ, $\bar{l}_r$, $\bar{l}_r^2$, $\bar{l}_i$ and $\bar{l}_i^2$ are the first and second moments of the relevant epoch and irrelevant epoch, respectively, and can be computed from their distribution.

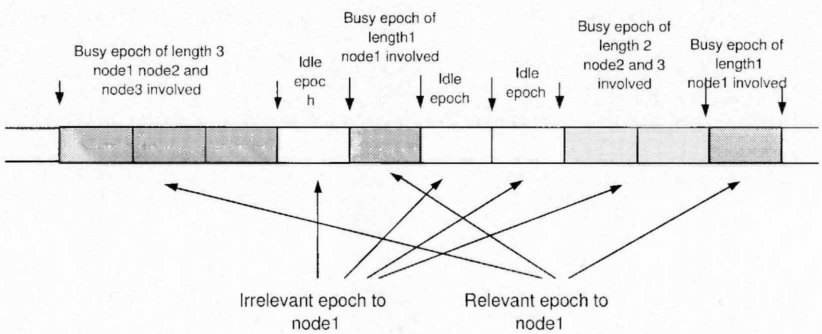

Figure 5.4 Epoch flow and types of epochs (busy epoch and idle epoch; relevant epoch and irrelevant epoch

5.6 Energy Consumption and Lifetime of the Network

For a crucial sensor node $s_i \in \mathcal{C}$, use $E_{i,init}$ to denote the initial energy of the node, $E_{i,s}$ to denote the energy needed to sense data (one bit), $E_{i,p}$ to denote the energy needed for data processing (one bit), and $E_{i,Rx}/E_{i,Tx}$ to denote the energy needed for receiving and transmitting the one bit data, respectively.

Since different collision separation methods are utilized in the collector, assume the $E_{i,s}$, $E_{i,p}$ are the same for all methods. The energy needed to receive a bit $E_{i,Rx}$ accounts

Table 5.1 Assumed Parameter for Crucial Nodes at Sensor Networks

Parameter	Value
Fade margin and Pass loss $P_l\alpha$	70dB
Thermal noise at collector N_t	-174dBm
Receiver noise at collector N_r	10dB
Signal bandwidth W	1MHz
Data rate R	1Mbps

for the receiver electronics energy dissipation. The energy needed to transmit a bit $E_{i,Tx}$ consists of two parts: the energy dissipation of the transmitter electronics $E_{i,txe}$, and the the RF transmit energy $E_{i,RF}$.

The energy per bit to noise ratio at the receiver is [2]

$$\frac{E_b}{N_0} = \frac{P_{RF}}{P_l\alpha} \cdot \frac{1}{WN_tN_r}$$

where P_{RF} is the RF transmission power, P_l is the large scale path loss, α is the average attenuation factor due to fading, W is the signal bandwidth, N_t is the thermal noise and N_r is the noise at the receiver known as the noise figure. In general, $P_l \propto \frac{1}{4\pi d^k}$, $2 \leq k \leq 4$.

The transmit power $P_{i,RF}$ can be written as

$$P_{i,RF} = P_l\alpha WN_tN_r\frac{E_b}{N_0} \tag{5.22}$$

The assumed parameters are given in table 5.1.

In the sensor network, collision happens when the number of the active crucial nodes is greater than the number of the antennas at the collector ($K > M$ at antenna array scheme and $K > 1$ at single antenna scheme), collided packets will be retransmitted for collision separation, and the retransmission time depends on K. The average RF energy required to transmit a bit for each node is a function of the number of the active nodes, one defines it as $E_{RF}(K)$

$$E_{RF}(K) = \frac{1}{K} K P_{RF} \cdot T_k = P_{RF} \cdot T_k \tag{5.23}$$

where $T_k = KT$ in NDMA scheme, and for SNDC approach $T_k = LT$. Then

$$E_{Tx}(K) = E_{RF}(K) + E_{txe}$$

Define the probability of a node's buffer being empty at the beginning of an epoch as P_{emp} [27], the probability of that K nodes are active is $P_a(K)$

$$P_a(K) = \binom{J}{K} (1 - P_{emp})^K \, P_{emp}^{J-K}$$

The average energy consumption for transmitting per bit per node is

$$E_{Tx} = \sum_{K=0}^{J} E_{Tx}(K) P_a(K)$$

Assume the average traffic rate in the sensor network is λ, λ_g and λ_{re} are the rate of traffic generated and relayed by s_i, the traffic generated by the crucial node is assumed to be the same for all nodes in the network and $\lambda_g = \lambda$, the traffic relayed by the crucial node is

$$\lambda_{re} = \frac{N_{total} - J}{J} \lambda$$

The power of node s_i is

$$\begin{aligned} P_i &= (E_{i,s} + E_{i,p} + E_{i,Tx}) N \lambda_{g,i} \\ &+ (E_{i,Rx} + E_{i,p} + E_{i,Tx}) N \lambda_{re,i} \\ &\geq E_{i,Tx} N (\lambda_{g,i} + \lambda_{re,i}) + E_{i,Rx} N \lambda_{re,i} \\ &= P_{i,Tx/Rx} \end{aligned} \tag{5.24}$$

The bound of the lifetime for node s_i is

$$t_i \leq \frac{E_{i,init}}{P_{i,Tx/Rx}}$$

The lifetime of the network is

$$t_{net} = \max\{t_i | s_i \in \mathcal{C}\} \tag{5.25}$$

5.7 Simulation Results

To observe the performance of the space and network assisted diversity multiple access method, it is compared with the pure NDMA method through simulation. Consider a slotted data communication system, the total number of node in the network is $N_{total} = 200$, the number of crucial nodes is $J = 32$, and the nodes' ID sequences gold code with code length $Q = 31$. The number of the receive antenna is $M = 2$. The transmission packets are fixed length of $N = 424$ bits (equal to the length of an ATM cell).

5.7.1 Error Performance Simulation

Two groups of experiments are carried out. In the first, the number of active transmission nodes is fixed $K = 5$, the SNR change for different approach. In the second, the simulation are carried under four SNR cases:

- 5 dB;
- 10 dB;
- 20 dB;
- 30 dB;

Under each scenario, the number of the active transmission nodes in the system changes. Figure 5.5 shows the simulation result of bit error rate versus signal to noise ratio. In this case, it is observed that with MMSE separation and the space and network diversity approach has the best performance.

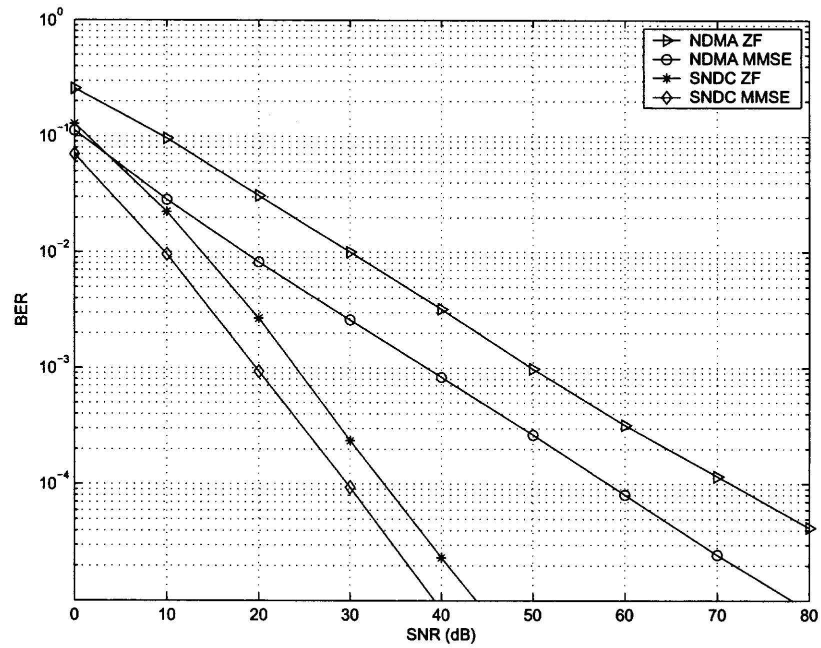

Figure 5.5 Performance comparison (BER versus SNR) between different collision resolution approaches. System parameters: $J = 32$, $M = 2$, and the number of active transmission nodes $K = 5$.

5.7.2 Goodput and Delay Performance Simulation

The analytical results and simulation results of goodput versus total traffic load according to (5.15) are shown in Figure 5.6 and Figure 5.7. Figure 5.6 and Figure 5.7 show the goodput versus total traffic load λJ corresponding to SNR from 5dB to 30dB. We present two results: the SNDC and the NDMA. The performance the of SNDC is better than NDMA only, especially in low SNR. From the comparison between the analytical and simulation results, the simulation results are in good agreement with the analytical expressions.

The delay performance is shown in Figure 5.8 and Figure 5.9 as a function of the traffic load. The analytical and simulation results demonstrate that the delay performance of the NDMA and space and network combining is much better than TDMA and pure

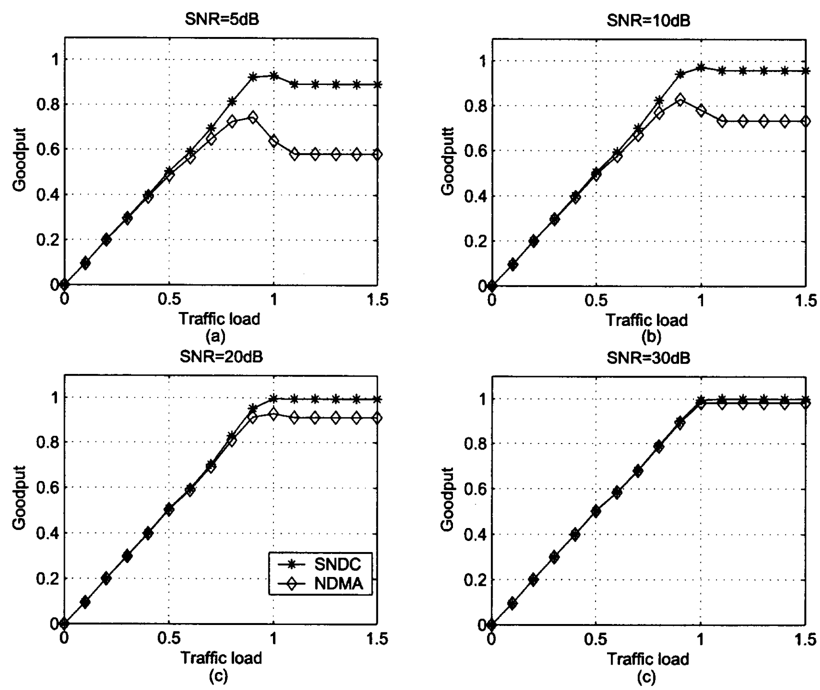

Figure 5.6 Analytical result: goodput vs. traffic load with between different collision resolution approaches. System parameters: $J = 32$, $M = 2$ (a) 5dB (b) 10dB (c) 20 dB (d) 30 dB

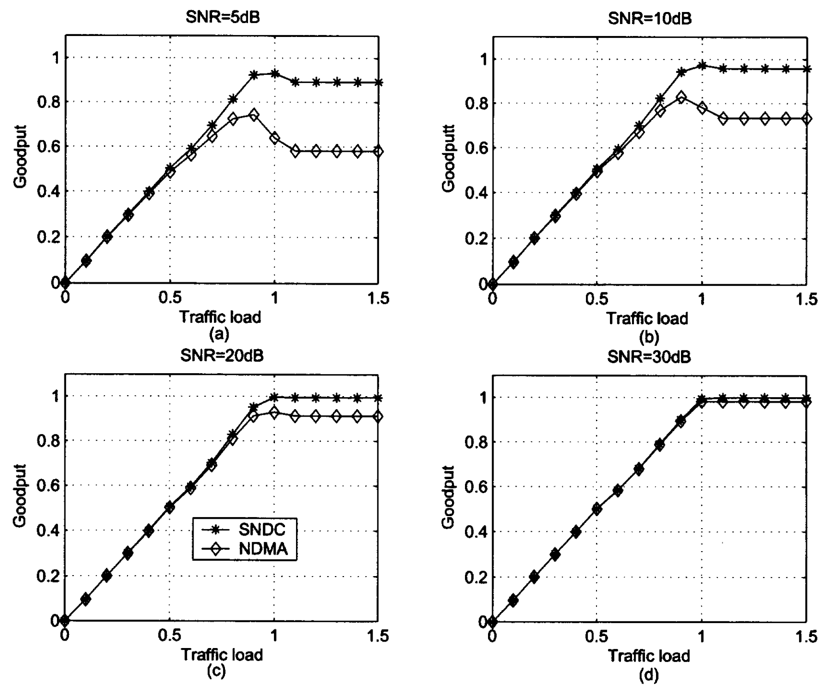

Figure 5.7 Simulation result: goodput vs. traffic load with between different collision resolution approaches. System parameters: $J = 32$, $M = 2$ (a) 5dB (b) 10dB (c) 20 dB (d) 30 dB

ALOHA. We may see the lowest latency property of the space and network combining approach comparing with other approaches.

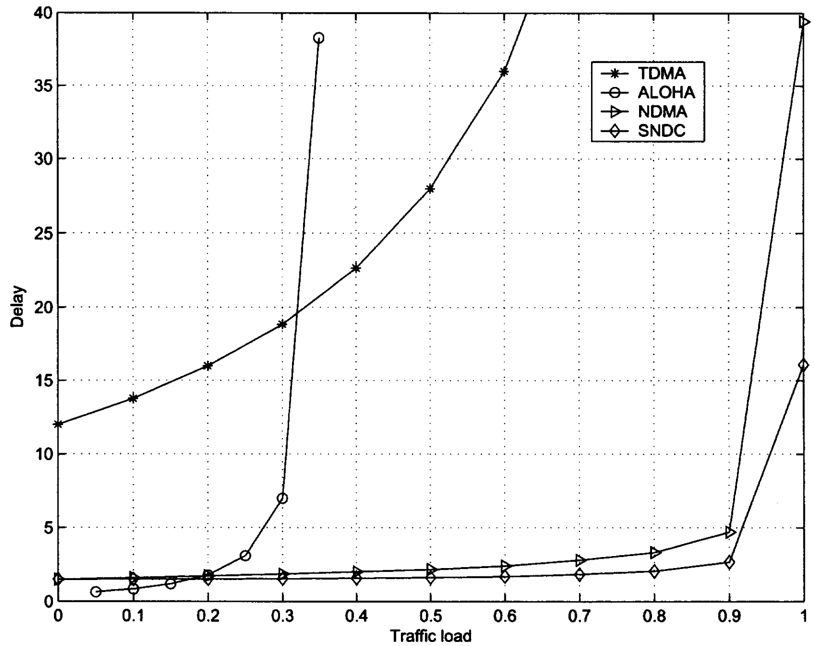

Figure 5.8 Performance comparison (delay vs. traffic load) among different approaches. (analytical results)

5.7.3 Energy Consumption and Network Lifetime

Let us assume The initial energy at each crucial node $E_{init} = 6J$ [57]. Figure 5.10 and Figure 5.12 show the simulation result for BER vs. transmitting power. It is important to note, the higher the transmission power, the lower the BER for the same method. To achieve the same BER, the MMSE and diversity combining scheme needs the lowest transmission power, especially under large active user number scenario.

Figure 5.11 and Figure 5.13 show the average energy consumption for transmitting a bit vs. BER when active nodes number is fixed. It is shown that more energy is needed to obtain the better BER performance for each approach, and the SNDC with MMSE separation scheme consumes the least energy.

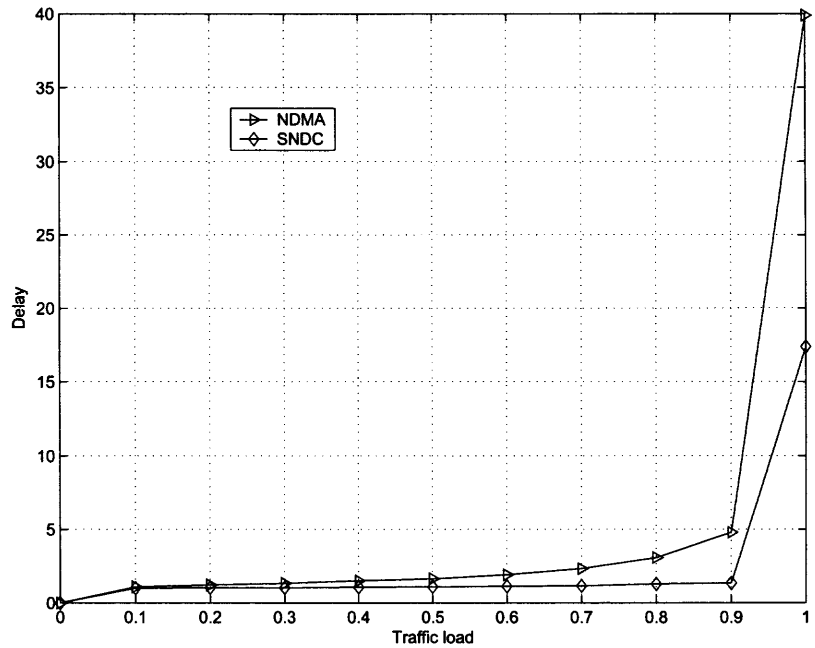

Figure 5.9 Performance comparison (delay vs. traffic load) among different approaches. (simulation results)

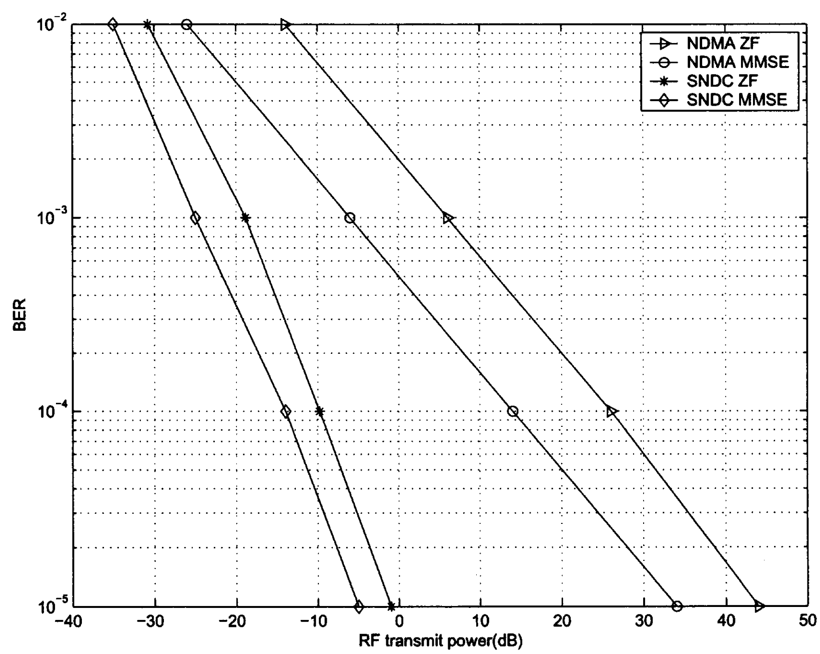

Figure 5.10 Bit error rate vs. transmission power using various of transmission methods (active user number=5)

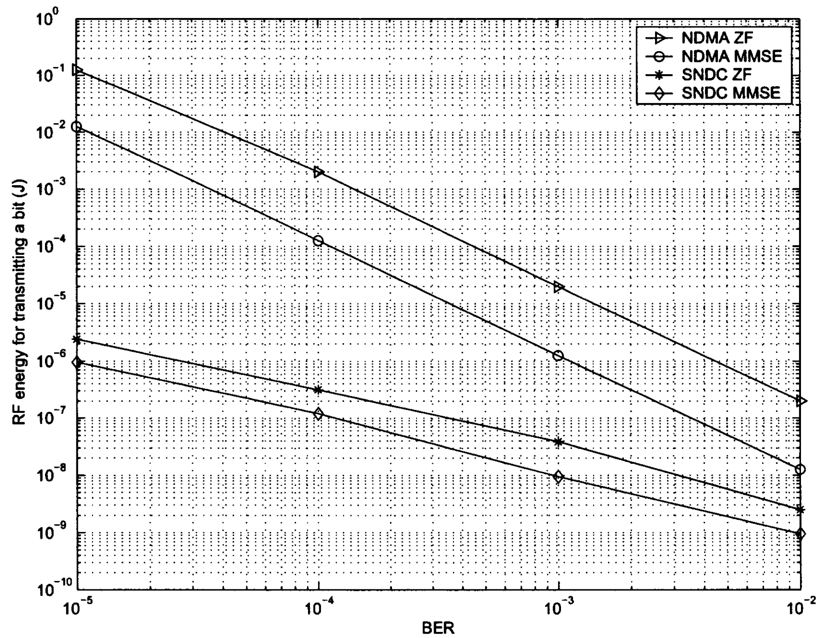

Figure 5.11 The energy per bit vs. bit error rate using various of transmission methods (active user number=5)

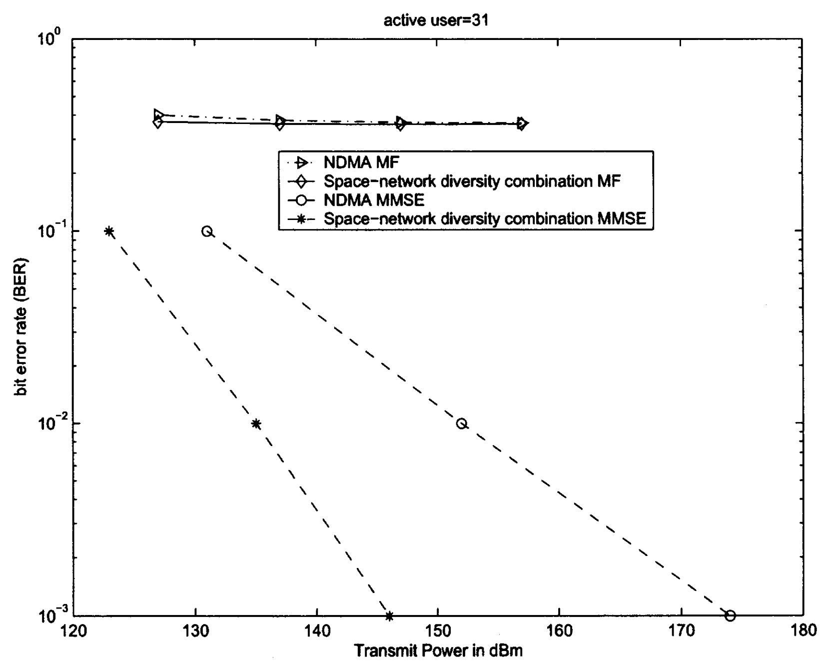

Figure 5.12 Bit error rate vs. transmission power using various of transmission methods (active user number=31)

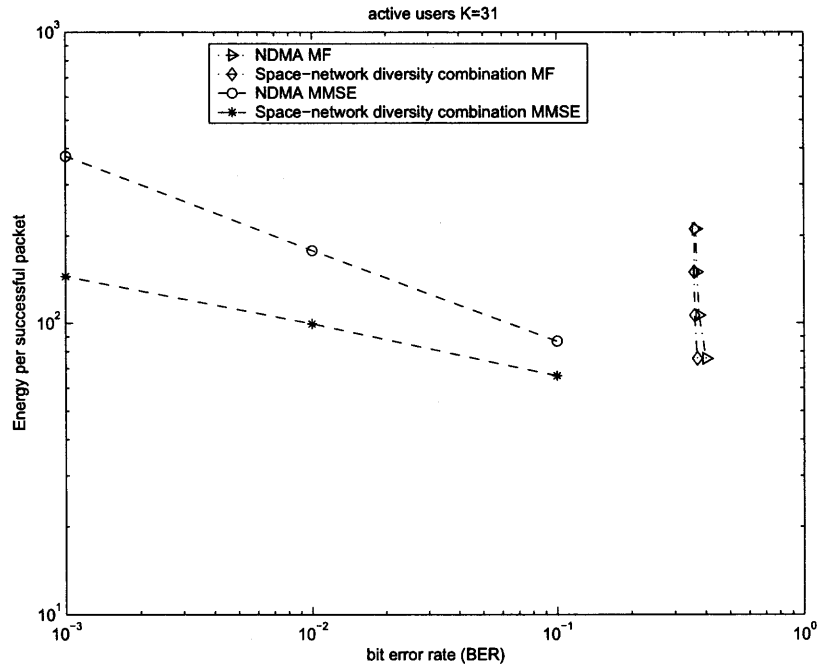

Figure 5.13 The energy per bit vs. bit error rate using various of transmission methods (active user number=31)

In Figure 5.14 and 5.16, one can see the energy consumption (transmission and receiving) increase with the traffic load, and energy consumption of the SNDC with MMSE separation method is much smaller than the others, especially when the lower BER is want to be achieved.

Figure 5.15 and 5.17 show the simulation results of the network lifetime vs. traffic load. The lifetime decrease when traffic load increase, and the lifetime of the SNDC with MMSE separation method is much larger than the others, especially when the lower BER is want to be achieved.

5.8 Conclusions

A new cross-layer design approach for network diversity is presented in this chapter. The proposed collision resolution scheme to multiple access in wireless sensor network is based on the combination of space and network assisted diversity. The diversity is fully exploited

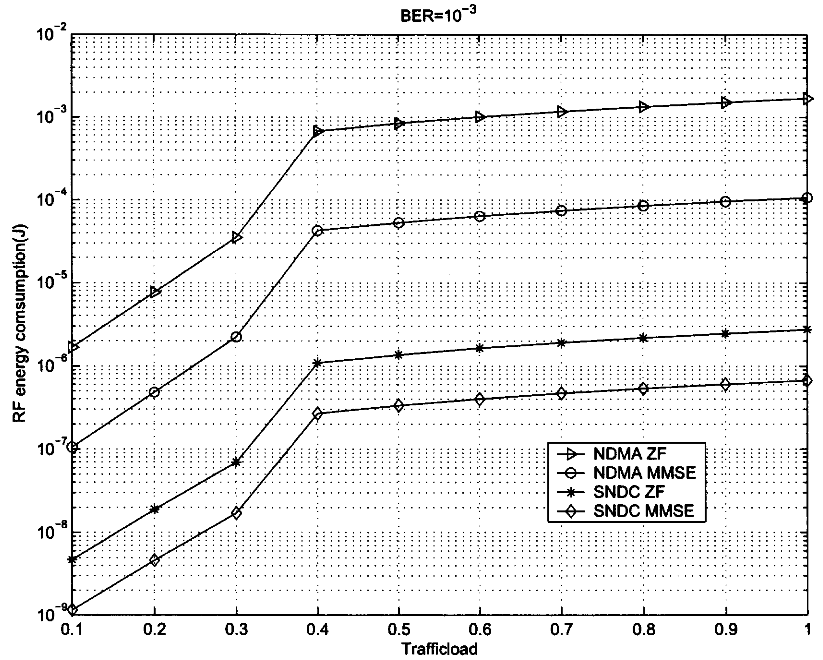

Figure 5.14 The energy consumption vs. traffic load using various of transmission methods (BER=10^{-3})

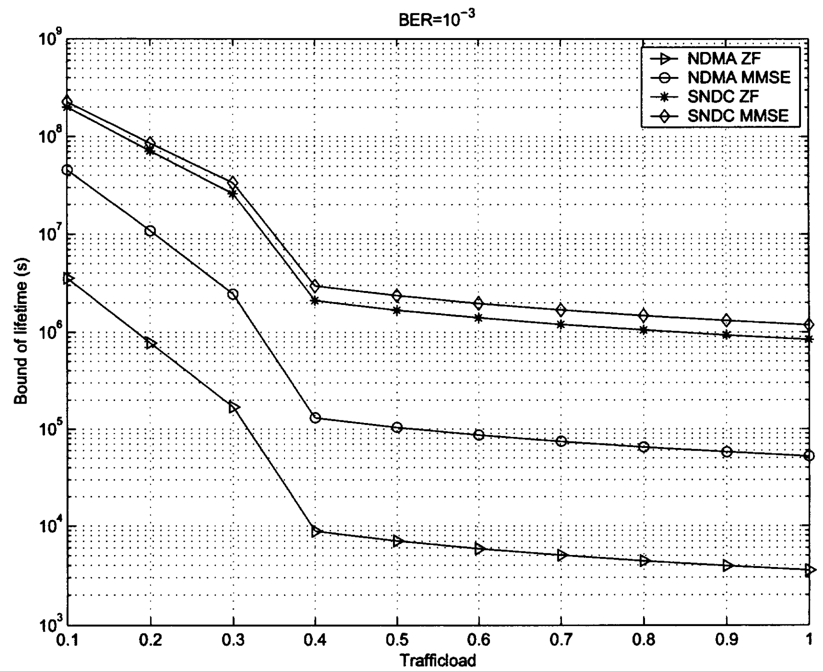

Figure 5.15 The lifetime vs. traffic load using various of transmission methods (BER=10^{-3})

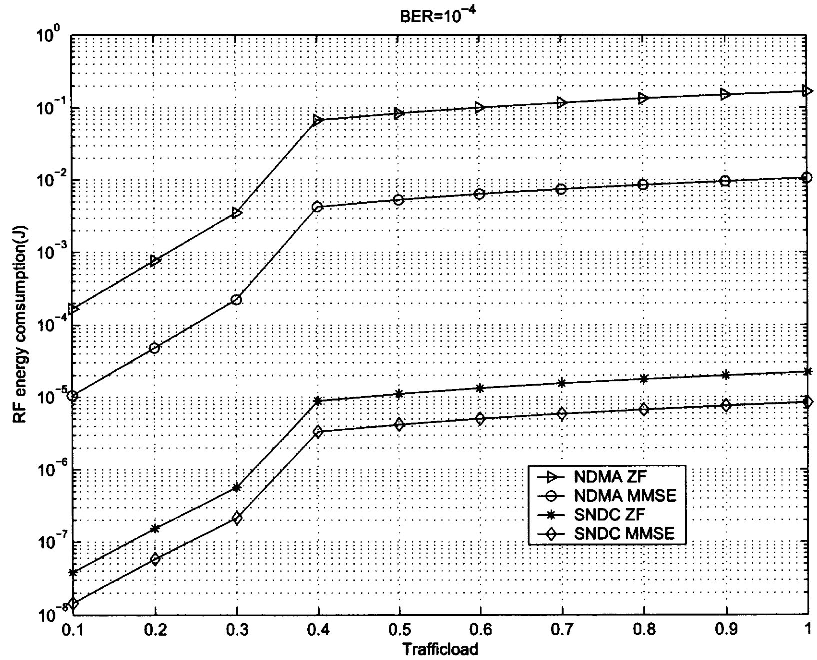

Figure 5.16 The energy consumption vs. traffic load using various of transmission methods (BER=10^{-4})

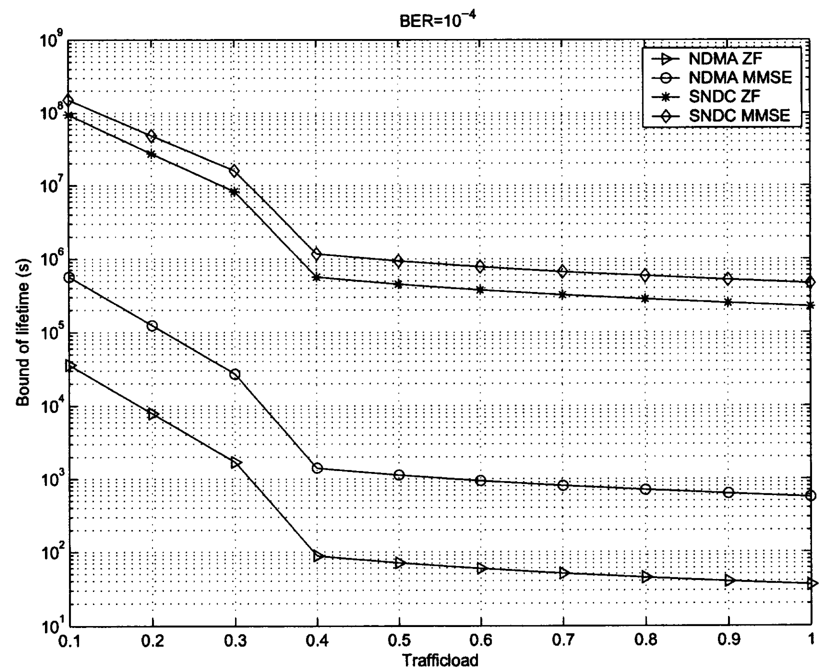

Figure 5.17 The lifetime vs. traffic load using various of transmission methods (BER=10^{-4})

by the receiver for collision resolving and package separation. It is demonstrated that this approach can extract the useful information from collided packets. Compared the the network-only assisted diversity approach with proposed space and network diversity, the latter improves the BER performance. The space and network combining approach also provides higher goodput and smaller delay.

CHAPTER 6

SUMMARY AND FUTURE WORK

6.1 Summary

Sensor network is a new challenging research area with many potential applications: smart space, environment sensing and monitoring, military and civilian applications, and entertainment. However, wireless sensor networks is fundamentally different from traditional wireless networks (cellular network, wireless LAN and wireless Ad hoc). Because of the constraints of hardware, energy, cost and computational ability, sensor networks present various design, implementation and deployment challenges. In this dissertation, several issues associated with the energy efficient and cross-layer design for sensor networks were investigated.

Chapter 2 introduces the cooperative space-time coding and the energy-efficient cooperative routing for cross layer design in multi-hop wireless sensor networks. Selected multiple nodes according to the link quality act as the transmitting and receiving antenna arrays. The orthogonal space-time code block is used to provide transmission diversity, and the sink uses a maximum ratio combining (MRC) together with its neighbors to make symbol decision. This research finds that the new scheme is capable of overcoming the multipath fading and reducing the interference. It is also demonstrated that the cooperative scheme is energy efficient and robust.

In Chapter 3, the dissertation introduces the differential space-time coding and the cooperative relay for cross layer design in multi-hop wireless sensor networks. The differential space-time code block is used to provide transmission diversity and avoid system complexity for channel tracking, the sink then uses a differential decoder to make symbol decision. The research finds that the new scheme is capable of overcoming the multipath fading and reducing the interference while improving the throughput and delay performance significantly.

Further more, the impact of network resource constraints on the performance of multi-hop sensor networks with cooperative relay is investigated. This dissertation models the cooperative relay method for sensor networks using a Markov chain and an M/G/1 queuing system, and studies the system performance when infinite buffer and finite buffer are used. The analytical and simulation results indicate significant system improvements in terms of system capacity. Moreover, the go through delay and the packet drop probability are also improved compared to traditional single relay method.

A new cross-layer design approach for network diversity is presented in Chapter 5. The proposed collision resolution scheme to multiple access in wireless network is based on the combination of space and network assisted diversity. The diversity is fully exploited by the receiver for collision resolving and package separation. It is demonstrated that this approach can extract the useful information from collided packets. Compared the network-only assisted diversity approach with proposed space and network diversity, the later method improves the BER performance. The energy consumption for collision separation with SNDC assisted diversity in wireless network is analyzed and its performance is compared with NDMA method. The simulation results show that the new scheme can reduce the transmission power and the energy consumption.

6.2 Current and Future Work

The following issues are interesting and challenging design relevant to future research and practical implementation.

1. Timing constrains are important, since sensor networks operate in the real world. In this proposal, the cooperative relay bare are selected on the link quality only, and it is difficult to guarantee real-time properties. The routing algorithm for choosing loop free multipath routing based on time constrain should be researched in the future.

2. The differential STBC technique can provide spacial diversity and the receiver can detect the desired signal without the channel information. The data receiving and relay based on the two by two STBC matrix at each hop, however it is hardly to find such perfect route in practical environment. The adaptive relay scheme based on the real network topology should be studied in future research.

3. The SNDC method can separate the collided packets and get the desired signal. In the energy consumption and lifetime analysis, it is assumed that the crucial nodes are dissipate the same transmission energy. The more practical energy consumption model based on the position of each crucial nodes and the distance between the crucial nodes and the collector should be considered in the future research.

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