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Reliable and Energy-Efficient Cooperative Transmission in Wireless Sensor Networks

by

Wenying Zheng

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Submitted to the Faculty of Graduate Studies and Research
through Electrical and Computer Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science at the
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ABSTRACT

In this thesis, we propose a cooperative relay scheme for multihop communications in wireless sensor networks. The scheme investigates node cooperation in conjunction with power control to conserve transmission energy and improve communication reliability in the presence of fading. By using relay nodes that are located between transmitter and receiver to assist packet delivery, the scheme is capable of reaping both spatial diversity gains and pass-loss savings. Local channel information is explored in relay selection process and power control to reduce the energy of data packet transmission. Moreover, a cooperative ARQ is incorporated to improve packet retransmission efficiency. We analyzed packet delivery ratio and energy consumption, and observed good agreement between analytical and simulation results. In simulations, we compared different cooperative and non-cooperative schemes and examined effects of various factors. Our simulations and analyses show that the proposed scheme improves energy efficiency, packet delivery ratio and extends nodes' battery lifetime.

ACKNOWLEDGMENTS

First and foremost, I would like to thank my advisor Dr. Kemal Tepe for his guidance and tremendous support which lead to the successful completion of this thesis. He has shown me the path to research and the critical aspects involved in research. He has instilled in me a state of confidence to undertake any challenges in the field of scientific research. His advice and feedback about my research has greatly enhanced this work. I am also very grateful to my committee member Dr. Alioune Ngom and Dr. Huapeng Wu for their insights and valuable suggestions on this work.

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Finally, I would like to thank my dear parents Songling Zheng and Renyuan Li, my brother Wenjun Zheng, my sister-in-law Xiaoli Xu and my uncle Yuan Li for their endless support, understanding and love.

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CHAPTER I

INTRODUCTION

I-1 Overview of WSNs

Ongoing developments in micro-electro-mechanical systems (MEMS) technology, wireless communication and digital circuitry have spawned extensive research in wireless sensor networks (WSNs) [1]. In typical sensor networks, a large number of small, inexpensive and multifunctional sensor nodes are scattered in a field. Each of these sensor nodes has the capabilities to interact with environment by sensing, data producing and then route the data back to the data collector (sink) by a multihop infrastructureless architecture. The sink may communicate with the task manager node via Internet or satellite. Figure 1 shows the communication architecture of a typical wireless sensor networks.
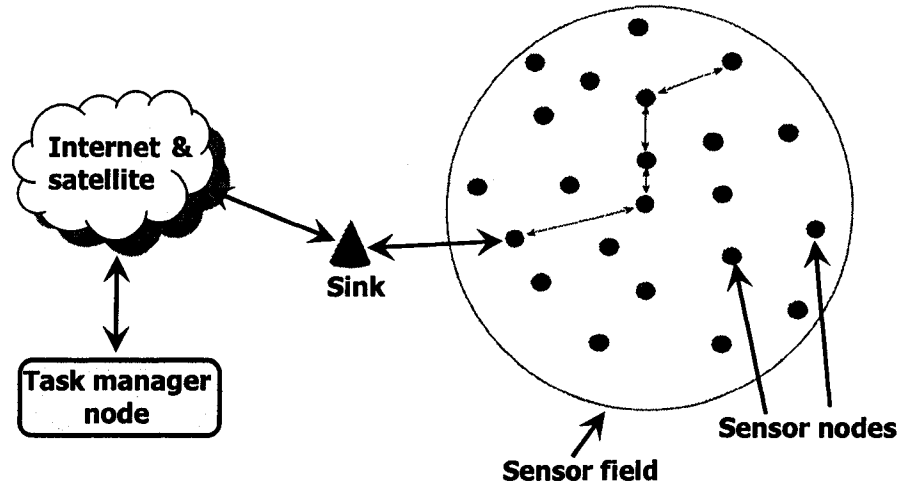
Figure 1: Communication architecture of wireless sensor networks.

Wireless sensor networks have many practical applications, ranging from military surveillance to disaster relief operations, from habitat monitoring to corrosion detection in large structures. Deployment of sensors on a battlefield can reduce the need for

1

soldiers to put themselves in danger (see Figure 2). Some sensor nodes can be deployed in a forest to report the exact origin of wildfire before it is spread uncontrollable. Bridge inspectors will no longer need to climb to dangerous heights to examine corrosion, since sensors will detect conditions. Another example of using wireless sensor networks is to gain an understanding of the number of plant and animal species that live in a given habitat.
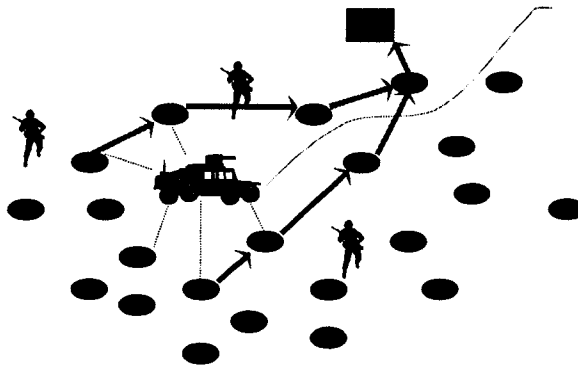
Figure 2: Application example of wireless sensor networks: battlefield surveillance.

Although the application types of wireless sensor networks vary in a wide range, some common features are shared among most application examples:

- Sensor nodes are densely deployed and node density will vary in different places and times.

- Sensor nodes are highly energy-constrained.

- Sensor nodes are simple and inexpensive devices and prone to failure.

- Topology of a sensor network changes frequently.

These features distinguish wireless sensor networks from other mobile networks and make the design of sensor systems a very challenging task.
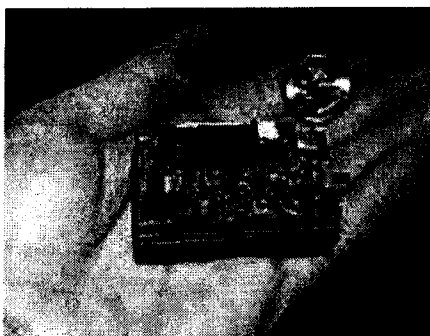
Figure 3: An example of sensor node: a Berkeley mote. Sensor node is small in size and usually has low cost and low power.

I-2 Problem Statement

An essential limiting factor in wireless sensor networks is energy consumption. In many scenarios, sensor nodes will have to rely on a limited supply of energy. Replacing these energy sources in the field is usually not practicable. Simultaneously, a wireless sensor network must operate at least for a given mission time or as long as possible. Hence, energy conservation plays a very important role to maximize the network lifetime – the duration for which sufficient numbers of nodes in the system have ample energy to provide the desired service.

Today's sensor networks make use of radio links for communication. Wireless communication has been identified as the dominant energy-consuming operation in WSNs, which makes energy efficiency an important figure of merit in the design of wireless communication techniques in sensor networks.

Another major challenge in the design of sensor networks is link reliability [2]. Since sensor nodes are linked by wireless medium, wireless links suffer channel variations due to fading, shadowing, interference, mobility and node failures, causing high error rates in wireless communication. Unsuccessful packet delivery requires packet retransmission. In flat fading environment, such as sensor networks, it is quite possible

that a link in fade long enough that data transmission will fail in spite of multiple retries, is thus waste of energy. On the other hand, most applications of today's sensor network , such as target tracking, machine monitoring and fire detection, etc., requires high data precision and the information collected by sensor nodes conveyed reliably to the sink. These requirements pose further challenges on the design of energy efficient and reliable transmission techniques in the wireless sensor networks.

I-3 Thesis Organization

In this thesis, we propose a cooperative transmission scheme to improve energy efficiency and link reliability of multihop communications in wireless sensor networks.

The thesis is organized in five chapters. Chapter II explains concepts of the techniques used in this work and provides a survey of related work. Chapter III presents the proposed cooperative transmission scheme. This includes the description of system and energy model, transmission power control approach, relay selection process, cooperative data transmission and cooperative ARQ. Chapter IV deals with performance analysis and simulation results, where packet delivery ratio and energy consumption are analyzed and compared to simulation results. In simulations, different cooperative and non-cooperative schemes are compared, effects of various factors are examined, and an extensive discussion of simulation results is performed. Finally, Chapter V concludes the thesis and identifies several open research problems arising from this work.

CHAPTER II

BACKGROUND AND RELATED WORK

II-1 Cooperative Diversity

Diversity is a powerful technique to mitigate fading and improve robustness to interference. Spatial diversity is particularly attractive because it provides diversity gain without expenditure of transmission time or bandwidth. These gains are typically realized through the use of multiple antennas at the transmitter and/or receiver side [3]-[6]. Unfortunately, physically implementing multiple antennas on the small and energy-limited sensor node may not be practical. On the other hand, sensor nodes are scattered in a field, which creates the inherent spatial redundancy that could be exploited. A new way of realizing spatial diversity gain has been introduced under the name of cooperative diversity. It includes a set of techniques that exploit the potential of spatially dispersed terminal antennas to improve communication reliability. The core idea is that multiple nodes (sensors) in a network cooperate to form a virtual antenna array realizing the spatial diversity gain in a distributed fashion. The achieved diversity gain enables the use of less transmission power for the same bit/packet error rate performance thereby improving energy efficiency. The cooperative transmission generally operates in two phases: (i) source transmits to relays and destination, and (ii) relays transmit to destination, as shown in Figure 4. Depending on the way that relays transmit to destination, there are two cooperative transmission approaches: (i) repetition-based, where relays transmit to destination on orthogonal sub-channels (e.g. in different time slots), and (ii) space-time coded, where relays utilize space-time code (STC) to transmit simultaneously on the same sub-channel.

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Phase I

S → R, D

Phase II

R → D
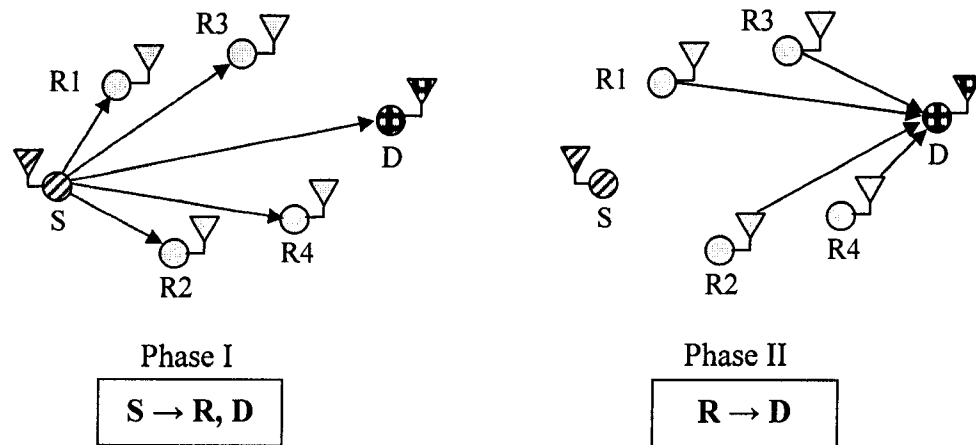
Figure 4: Cooperative transmission typically operates in two phases: (i) source transmits to relays and destination; (ii) relays transmit to destination.

Earlier research work on cooperative diversity was reported in [7]-[9]. Sendonaris et al. [7] suggested cooperation between pairs of wireless users and showed that cooperative users in a wireless network can achieve higher rates and the communication link is more robust to channel variations. Laneman et al. [8] [9] developed different decode-and-forward and amplify-and-forward protocols to achieve diversity. In [8], several two-stage relay strategies were proposed and studied, including fixed relaying, selective relaying, and incremental relaying. In [9], these schemes were extended to large networks and both repetition-based and space-time-coded cooperation were considered.

Recent research investigations that consider node cooperation in wireless ad hoc and sensor networks include cooperative MIMO techniques [10]-[13], cooperative routing [14]-[17], and diversity forwarding [18]-[21].

Multi-input multi-output (MIMO) techniques are very effective in improving performance of wireless systems in the presence of fading [36]. Cooperative MIMO

techniques allow multiple nodes to cooperate in signal transmission and/or reception. Cui and Goldsimth [10] proposed a cooperative MIMO technique where multiple nodes within a cluster cooperate in signal transmission and reception with optimal rate. The authors showed that cross-layer design coupled with node cooperation and rate adaptation can significantly improve the energy-delay tradeoff in wireless networks. This work was later extended in [11], where an energy-efficient virtual MIMO-based communication architecture was proposed and the impact of the training overhead and fading coherence time was analyzed. Li *et al.* [12] investigated space-time-block-coded (STBC) cooperative transmission within LEACH protocol and studied the problem of overhead and synchronization. The authors showed that with proper design, cooperative transmission can enhance energy efficiency and prolong sensor network lifetime. Cheng and Kung [13] proposed a relay scheme in conjunction with maximum ratio combining (MRC) and Alamouti space-time codes that exploits geometric gain resulting from the location of properly deployed relays to extend the battery lifetime of the network.

Cooperative routing, as a new term under the cross-layer design paradigm, explores the interaction between cooperative diversity in physical layer and routing in network layer. Luo *et al.* [14] proposed three cooperative routing approaches: relay-by-flooding, relay-assisted routing and relay-enhanced routing and evaluated the outage probability for three relay schemes: simple relay, space-time-coded relay and best-select relay. Their results indicate a significant performance improvement in outage probability and achieved rate. Liu and Ge [15] proposed a space-time coding and link quality based cooperative routing scheme to achieve high throughput in multihop WSNs. Chen *et al.* [16] considered the issue of cooperative communication and routing in fading channels

and showed that significant spatial diversity gains are achievable with multi-node cooperation. Xie *et al.* [17] incorporated cooperative transmission into route selection and demonstrated power savings of their cooperative routing strategy over the simple multihop routing.

Valenti and Correal [18] investigated the inherent spatial redundancy in the dense network and introduced the macrodiversity-combing concept by using neighbor nodes as relays to forward packet from the source to the destination. The authors illustrated that an order of magnitude reduction in transmit power is achievable. Wang *et al.* [19] proposed a scheme that exploits path diversity to improve the reliability and energy efficiency of packet forwarding in multihop ad hoc networks. The scheme utilizes RTS/CTS handshaking messages to measure channel quality while selecting the qualified candidate forwarding node. Larsson [20] introduced an adaptive forwarding scheme, denoted selection diversity forwarding (SDF), where nodes select best relay path based on local instantaneous knowledge at the time of forwarding packets. The author showed that SDF increases forward progress and throughput, especially in fading channel conditions. Recently, Larsson and Johnasson [21] proposed an opportunistic forwarding scheme, denoted multiuser diversity forwarding (MDF). The scheme jointly chooses relay node, data flow and transmission rate taking advantage of channel characteristics. Compared to SDF, MDF is shown to be more power efficient and yields a substantial throughput increase.

II-2 Energy-Oriented Power Control Approaches

Another technique for energy-efficient communication is to use power control to conserve energy. Instead of every node using the same transmission power, a transmitting

node will use minimum transmission power level that is required to communicate with the desired receiving node. This ensures that the necessary and sufficient transmission power is used over each link, hence, conserves energy and extends node's battery life. This has the added advantage of reducing interference with other on-going transmissions.

Power control approaches that aim at reducing energy consumption of nodes and prolong the lifetime of network have been utilized in the design of power-aware routing protocols. PAMAS is one such minimum total transmission energy protocol. In PAMAS [22], nodes can dynamically adjust their power based on the link distance and the link cost is set to transmission power. Later in [23], new metrics which consider residual energy at nodes are formulated for path selection. It is shown that the mean time of node failure is increased significantly by using these new metrics. Another power-aware routing protocol is PARO (power aware routing optimization) [24]. According to PARO protocol, a candidate intermediate node monitors an ongoing direct communication between two nodes and evaluates the potential for power savings by inserting itself in the forwarding path to reduce overall energy consumption in the network.

Power control is also utilized in the design of transmission techniques to reduce energy consumption. Pursley *et al.* [25] designed an adaptive transmission protocol, which utilizes channel information to adjust power and information rate of the transmitting signal to conserve energy. Kubisch *et al.* [26] proposed two distributed power control algorithms for controlling the number of neighbors to ensure network connectivity and increase the network lifetime. Tralli [27] proposed relay schemes based on node cooperation and coding and utilized power control to reduce the energy

consumed for transmission. An overview of various transmission power control approaches can be found in [28].

II-3 Node Cooperation with ARQ

Automatic repeat request (ARQ) protocol is typically employed in the data link layer that requires retransmission for the packets received in error. The basic idea of ARQ protocols can be described as follows: The transmitter prepends a header and appends a checksum to a data block. The resulting packet is then transmitted. The receiver checks the packet's integrity with the help of checksum and provides some feedback to the transmitter regarding the success of packet transmission. On receiving negative feedback, the transmitter performs a retransmission. In practice, the maximum number of retransmissions is usually limited so as to minimize the delay and buffer size. Such variant ARQ is called truncated ARQ protocol.

Dai and Letaief [29] proposed a cross-layer design which combines cooperative diversity in the physical layer and truncated ARQ in the link layer to improve system throughput. In the proposed scheme, when packet delivery fails, certain nodes are selected as relays based on channel conditions using CRC and then the source node and selected relays jointly retransmit the packet utilizing a STBC code. Monti *et al.* [30] described an ARQ-C protocol for the unique microwave recharged wireless sensor networks to yield reliable and fair data transmission from the sensor nodes to the base station. In the ARQ-C protocol, when the direct transmission from the sensor node to the base station fails, certain intermediate sensor nodes help during the retransmission process. The transmission power is optimized at each sensor node to increase the saturation throughput of ARQ protocol. Zhao and Valenti [31] introduced HARBINGER

(hybrid-ARQ-based intracluster geographic relaying) protocol to networks comprising multiple relays operating over orthogonal time slots in a block fading environment. The authors studied the information-theoretic performance limits of relay networks using generalized hybrid ARQ. Their results indicate a significant improvement in throughput and energy-delay tradeoff.

Motivated by above research work, in this thesis, we propose a cooperative relay transmission scheme, denoted cooperative transmission and ARQ retransmission, for multihop communications in wireless sensor networks. The scheme uses relay nodes in conjunction with transmission power control to assist packer delivery from source to destination in the presence of fading. Channel information in the physical layer is explored over each link and utilized in the transmission power control and relay selection process. Transmission power of each data packet is adjusted using RTS/CTS handshaking messages. The cooperative relays are selected based on the cost function which reflects both transmit and receive energy consumption as well as node's residual energy. When packet delivery fails, a cooperative ARQ scheme is incorporated, whereby the retransmitted packets do not come from the transmitting node but instead be sent from an intermediate node that is located between transmitting and receiving nodes and that overhears the packet transmission. Detailed description of the proposed scheme is presented in Chapter III.

CHAPTER III

COOPERATIVE TRANSMISSION & ARQ RETRANSMISSION

III-1 System and Energy Model

We consider a data collection sensor network, where a sensor node collects data from the observed source region and wants to transmit it to the remote sink via a multihop infrastructureless architecture. At any given time instant, nodes can be classified as live or dead depending on whether they have energy left or not. The live nodes can operate in one of the four states: (i) sensing and data producing; (ii) relaying received data; (iii) idling; (iv) sleeping with power down. All the nodes can change their states dynamically with time.

We assume the wireless channel is subject to frequency flat Rayleigh fading, which is suitable for slow-varying fading environment such as sensor networks. The physical wireless channel has instantaneous received SNR, given by

$$\gamma = \Gamma \cdot |h|^2, \tag{1}$$

where $|h|$ is the Rayleigh-distributed fading magnitude with $E\{|h|^2\} = 1$. The instantaneous SNR γ is a random variable with an exponential probability density function (pdf)

$$p_\gamma(\gamma) = \frac{1}{\Gamma} e^{-\frac{\gamma}{\Gamma}}, \tag{2}$$

and $\Gamma = E\{\gamma\}$ represents the average received SNR modeled as

$$\Gamma = K \frac{P_{tx}}{P_N} \left(\frac{d}{d_0}\right)^{-n}, \tag{3}$$

12

where P_{tx} denotes the transmission power, P_N is the additive noise power at the receiver (equal for each receiver), $d_0 = 1$ m is a reference distance, d indicates the transmitter-receiver separation, n is the path loss exponent, and K is the channel attenuation at the reference distance. For a 2.4GHz operating frequency, $K = \left(4\pi \times d_0 \times \dfrac{f_c}{c} \right)^2 \approx 10^4$.

In a typical sensor network, energy consumption can be largely categorized into two activities: (i) computation (such as sensing, data processing) and (ii) communication. Of two, communication is the most energy-intensive [1]. Energy conservation in this activity greatly improves the node's battery life, hence the lifetime of sensor network. The energy conservation model, shown in Figure 5, aims to formulate the energy consumption during the communication activity.

There are three major causes of energy depletion in a node during communication activity: (i) energy consumption for RF propagation; (ii) energy consumption in the transmitting hardware for operations such as encoding and modulation, and (iii) energy consumption in the receiving hardware for operations such as demodulation and decoding. For simplicity, we assume that the energy consumed in transmitter and receiver circuitry is same for all the nodes in the system, denoted by e_T^{elec} and e_R^{elec}, respectively. The energy consumed by transmitting a k-bit packet is modeled as

$$e^{tx}(k,d) = k \left(e_T^{elec} + \frac{P_{tx}(k,d^n)}{R_b} \right),$$

(4)

and the energy consumed by receiving a k-bit packet is given by

$$e^{rx}(k,d) = k e_R^{elec},$$

(5)

where $e_T^{elec} = e_R^{elec} = 50nJ/bit$, d is the Euclidean distance between transmitting and receiving nodes, P_{tx} denotes the packet transmission power from the transmit amplifier, n is the path loss exponent and R_b is the bit rate.
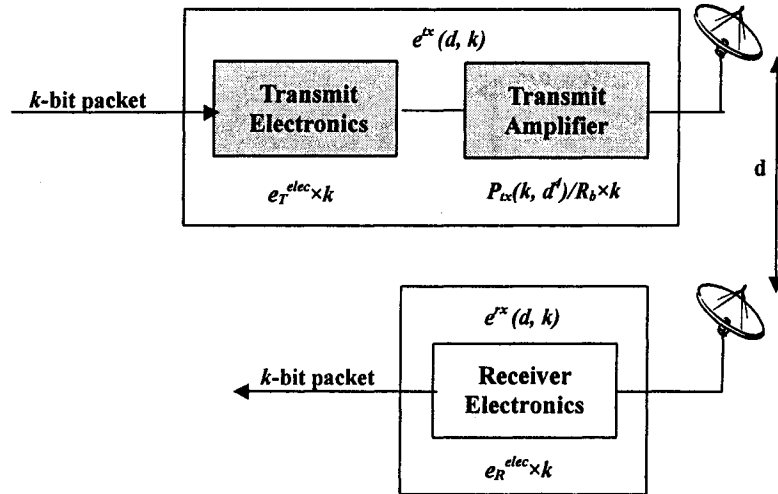
Figure 5: Energy consumption model.

The energy consumption model is adopted from [32], but there are two modifications: (i) the path loss exponent n is chosen to be four instead of two to capture the effect of low-lying antenna and near ground channel, which is typical in sensor network communications [33], and (ii) the transmission power of the transmit amplifier is explicitly expressed in the model because the transmit amplifier is the dominant energy-consuming part in the transmitter. We neglect any energy consumption that occurs when the node is in the sleep or idle state, and we also neglect the energy consumed for transmitting and receiving the acknowledgement message since it is much smaller in length than the data packet.

To conserve energy, we assume nodes in the sensor network are in sleep state for higher percentage of time and cycle on and off randomly. A perfect contention-free MAC protocol is employed in the link layer. We further assume a minimum-hop (MH) routing

path is initially established from the original sensor node in source region to the remote sink over a few active nodes as shown in Figure 6. Since each node is allowed to set its own sleep/wakeup schedule autonomously, some other nodes nearby each MH hop path may turn active during the data transmission. Using these intermediate nodes to assist packet delivery can improve transmission efficiency.
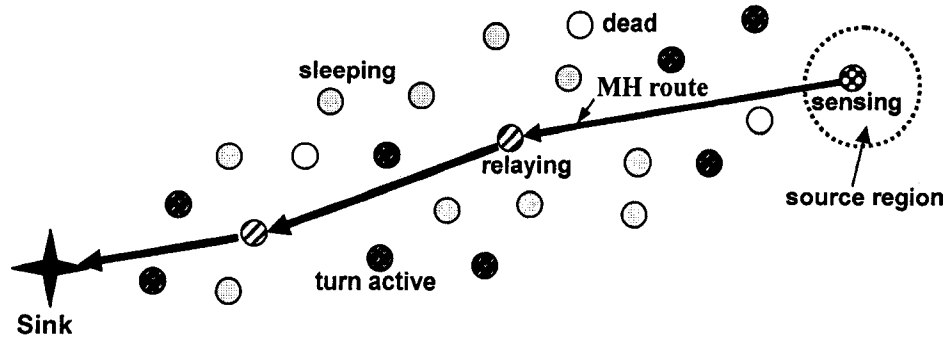
Figure 6: A MH routing path is established from the origin sensor node to the remote sink over a few active nodes. Some other nodes may turn active during data packet transmission.

Figure 7 illustrates the idea of cooperative transmission over one MH hop. There are three types of entities in this figure:

- Source (S) – transmitting node over one hop of the MH route.

- Destination (D) – receiving node over one hop of the MH route.

- Candidate relay nodes ($R1$ to $R6$) – intermediate nodes that turn active during data packet transmission.
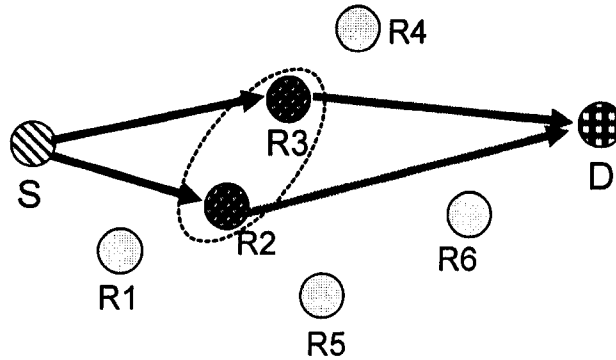
Figure 7: Cooperative transmission over one MH hop: a double-hop topology.

We assume all the nodes are sufficiently apart so that channels among them are statistically independent. Instead of direct transmission from source to destination, certain number of intermediate nodes are selected as relays to assist the data packet transmission. Thus, we replace the direct hop topology between source and destination by two smaller hops via the selected relays, which we call a double-hop topology.

Our cooperative transmission scheme operates in two steps: (i) relay selection and (ii) cooperative data transmission. Transmission power control is incorporated into the scheme to conserve energy of each data packet transmission.

III-2 Transmission Power Control

It is reported that the transmit amplifier consumes more than half of the total communication-related energy and the ratio is expected to increase in the future, as the processing components become more power efficient [28]. In the energy consumption model, the power consumed by the dominant transmit amplifier is directly proportional to the transmit signal, and thus it is of great interest to control the signal transmission power to increase the node's lifetime.

Suppose a packet is transmitted from node S to node D, the received power at node D can be formulated by

$$P_D^{rx} = P_S^{tx} \frac{g_{SD}}{d_{SD}^4}, \tag{6}$$

where P_S^{tx} is the transmission power at node S, d_{SD} is the distance between node S and node D, and g_{SD} is the channel random fading gain. We assume g_{SD} is stationary for the duration of the control and data packet transmission and receiver can obtain perfect channel knowledge.

We assume that a packet can be received without error if the SNR of the received signal is above a certain threshold (SNR_{th}) and that no information is received otherwise. Since the SNR is determined by the received signal power and the additive noise power (assumed to be equal at each receiver), a certain level of receiver sensitivity P_{rmin} (given in dBm) is required, which specifies the minimum signal power at the receiver needed to achieve a prescribed SNR_{th} or a prescribed bit/packet error rate performance.

We assume that all the nodes in the network are able to dynamically adjust transmission power across the links. Each node chooses the transmission power level for a link so that the signal reaches the destination node with the same constant received power (P_{rmin}).

The transmission power control in our cooperative scheme is accomplished by using MAC layer RTS-CTS handshaking messages with limited overhead. As illustrated in Figure 8, in order to adjust the transmission power of data packet, node A first sends RTS message at maximum power level (P_{tmax}) to node B. Node B measures the received power of RTS (P_{RTS}^{rx}) and determines the desired transmission power of data packet at

$$P_{data}^{tx} = P_{rmin} \frac{d^4}{g} = P_{rmin} \frac{P_{tmax}}{P_{RTS}^{rx}}, \tag{7}$$

Node B then sends P_{data}^{tx} back to node A with CTS message. Node A uses the new power to send the following data packet.
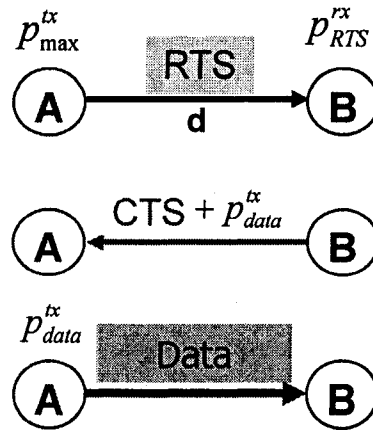
Figure 8: Transmission power of data packet is adjusted to minimum level using MAC layer RTS/CTS handshaking messages.

With this power control approach, the transmission power of each data packet is adjusted to the minimum level to be just enough to reach the intended receiver while still satisfying the prescribed bit/packet error rate performance. Since the data packet contains much more bits than the handshaking messages, significant energy savings can be achieved.

III-3 Relay Selection

The relay selection process exploits the broadcast property of wireless communication to select nodes that are best qualified to serve as relays in the packet delivery from the source to the destination.

When the source has data packet to send, it first broadcasts a RTS message at $P_{t\max}$. The RTS message contains how many nodes will serve as relays (denoted by J). Each node that receives the RTS examines: (i) its remaining energy level and (ii) its distance to the destination, and computes (iii) desired transmission power of data packet.

Based on the information, each node evaluates the cost of serving as relay and sends back CTS message attaching the desired data power. To avoid concurrent transmission while sending CTS, different time-window is applied at each node and the waiting interval is made proportional to the node's cost, i.e.,

$$Interval_{R_i} = Cost_{R_i} \times 100 \text{ msec.} \tag{8}$$

Consequently, nodes with smaller cost will send CTS at earlier time. Assume CTS message can be heard by all the other nodes and nodes have the capability to count the number of CTS transmission times. Only first J nodes need to reply and they are the selected relays. With this approach, both collision and unnecessary CTS transmissions can be avoided.

The cost function evaluated at each candidate relay node contains both link costs from source to relays and from relays to destination. Each link cost reflects both the transmit and receive energy consumption as well as the nodes' residual energy level, similar to the case in [34]. To be specific, we define the link cost from source to relay R_i as follows:

$$Cost_{SR_i} = \underbrace{e_{SR_i}^{tx} \left(\frac{E_S}{\underline{E}_S} \right)^{-x}}_{\substack{source \\ Transmission}} + \underbrace{e_{SR_i}^{rx} \left(\frac{E_{R_i}}{\underline{E}_{R_i}} \right)^{-x}}_{\substack{relay R_i \\ Reception}} = \left(e_T^{elec} + \frac{P_{r\min} P_{t\max}}{P_{R_i-RTS}^{rx} R_b} \right) \left(\frac{E_S}{\underline{E}_S} \right)^{-x} + e_R^{elec} \left(\frac{E_{R_i}}{\underline{E}_{R_i}} \right)^{-x}, \tag{9}$$

where E_S, E_{R_i} and $\underline{E}_S$, $\underline{E}_{R_i}$ denote initial and residual energy levels at source and relay R_i, respectively. x is a non-negative weighting exponent on the remaining energy. Note that the residual energy is normalized by the initial energy because sensor nodes can have different initial energy levels. $e_{SR_i}^{tx}$ is the energy expenditure during transmission and $e_{SR_i}^{rx}$ is the energy consumed during reception, as defined in (4) and (5) of the energy

consumption model. Similarly, the cost of the link originated from relay R_i to destination is given by

$$Cost_{R_iD} = \underbrace{e_{R,D}^{tx}\left(\frac{E_{R_i}}{E_{R_i}}\right)^{-x} + e_{R,D}^{rx}\left(\frac{E_D}{E_D}\right)^{-x}}_{\substack{relayR_i \\ Transmission \quad destination \\ Reception}} = \left(e_T^{elec} + \frac{P_{r\min}d_{R_iD}^4}{R_b}\right)\left(\frac{E_{R_i}}{E_{R_i}}\right)^{-x} + e_R^{elec}\left(\frac{E_{D_i}}{E_D}\right)^{-x}. \tag{10}$$

Hence, the cost for intermediate node R_i to serve as relay can be formulated as:

$$Cost_{R_i} = \underbrace{e_{SR_i}^{tx}\left(\frac{E_S}{E_S}\right)^{-x}}_{\substack{source \\ Transmission}} + \underbrace{\left(e_{SR_i}^{rx} + e_{R,D}^{tx}\right)\left(\frac{E_{R_i}}{E_{R_i}}\right)^{-x}}_{\substack{relayR_i \\ Reception+Transmission}}. \tag{11}$$

Note that the cost function (11) explores link quality from source to relays. This channel knowledge is obtained by exchanging RTS/CTS messages and is utilized in the computation of desired transmission power of data packet at the source. Since the link quality from relays to destination is unknown, only the distance information is used in the cost computation. By using this cost function, the node that are facing energy exhaustion and the nodes that may consume too much energy during packet transmission will be avoided to serve as relays.

III-4 Cooperative Data Transmission

After relay selection, source sends the data packet to the selected relays using the desired transmission power (maximum of the received J data power levels contained in CTSs). Because the relays are located closer to the source than the destination is, they can offload a major portion of transmission power consumed at the source. Moreover, relays can receive the data packet more reliably due to the relay selection process.

Next, selected relays forward the received data copies over uncorrelated channel to the destination. The aforementioned time-window approach can be used to avoid concurrent transmission. At the destination, different data copies are maximal ratio combined (MRC) to achieve spatial diversity gain. For the same prescribed packet error rate constraints, the achieved diversity gain enables the use of less transmission power at the relay nodes, hence improves energy efficiency.

When the destination receives the packet correctly, it sends a positive acknowledgement (ACK) message, otherwise, a negative acknowledgement (NACK) message is sent. We assume that ACK and NACK transmissions are error-and-delay free.

III-5 Cooperative ARQ

For reliable communications, the automatic repeat request (ARQ) protocol is typically employed in the data link layer to handle packet retransmission. The conventional ARQ scheme requires the transmitting node retransmit until the packet is successfully delivered or a preset retry limit is exceeded. In flat fading environment, such as sensor networks, the packet length is usually short as compared to the average fade duration. In that case, if a packet is hit by a deep fade, a retransmission will likely be hit by the same deep fade and is thus a waste of energy.

To improve packet retransmission efficiency, we introduce a cooperative ARQ scheme. Due to the broadcast nature of wireless medium, certain nodes located between selected relays and destination may overhear the data packet transmission, and one of them can be selected to retransmit the packet to the destination. We call this node the retransmission relay. The detailed process is described as follows.

When destination broadcasts a NACK message, nodes that have overheard the data packet send RTS messages to the destination at $P_{t\max}$. The waiting time to send RTS at each node can be made proportional to the link cost from the node to the destination. Destination measures received power of RTS ($P^{rx}_{RTS-R_i}$) and replies each RTS with CTS message attaching $P^{rx}_{RTS-R_i}$. Each candidate node then computes the desired data retransmission power and evaluates the cost of serving as the retransmission relay, given by

$$Cost^{retx}_{R,D} = \underbrace{e^{tx}_{R,D}\left(\frac{E_{R_i}}{E_{R_i}}\right)^{-x}}_{\substack{relayR_i \\ Transmission}} = \left(e^{elec}_T + P_{r\min}\frac{P_{t\max}}{P^{rx}_{RTS-R_i}R_b}\right)\left(\frac{E_{R_i}}{E_{R_i}}\right)^{-x}. \tag{12}$$

The one with the minimum cost will transmit the packet to destination using the desired power. For example, in Figure 9, nodes *R2* and *R3* are selected as cooperative relays and nodes *R4*, *R5* and *R6* overheard the packet transmission from nodes *R2* and *R3* to the destination. In case of packet delivery failure, node *R6* is selected to serve as retransmission relay. With cooperative ARQ, the packet retransmission are more energy efficient and reliable.
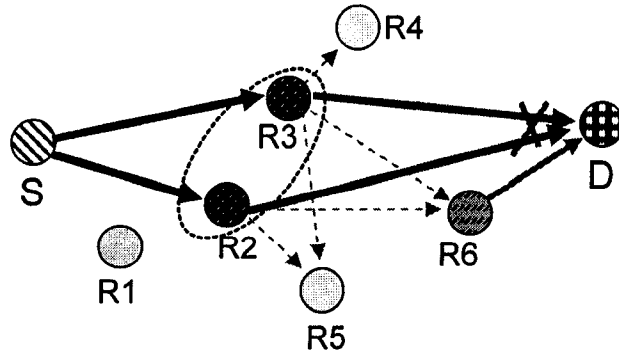
Figure 9: Cooperative ARQ: intermediate nodes help during packet retransmission.

In a sense, cooperative transmission and ARQ retransmission scheme provides a way to distribute energy consumption among multiple nodes to accomplish reliable and energy efficient data delivery in wireless sensor networks. The scheme simultaneously exploits two potentials offered by wireless relay systems: spatial diversity gains and path-loss savings. The spatial diversity gains are achieved since different data copies are transmitted over uncorrelated channels and diversity-combined at the destination. The path-loss savings are achieved because relays are located between the source and the destination, which shortens the length of individual hops and thus reduce the transmission energy consumption at both source and relays. Moreover, relays can receive the packet transmission by the source much more reliably than the destination. Since the relays are selected right before each data packet transmission, the scheme can be on-demand and hence adaptive to the frequent-changing characteristics of wireless sensor networks. Further, the scheme is able to alleviate the problem of excessive energy consumption at certain mission-critical node for a more balanced network lifetime.

CHAPTER IV

PERFORMANCE ANALYSIS AND SIMULATION RESULTS

IV-1 Packet Delivery Ratio Analysis

Consider the double-hop topology as shown in Figure 7. Assume N number of intermediate nodes are located between the source and the destination, and J of them are required to serve as cooperative relays ($N=6$ and $J=2$ in Figure 7). Let p_f denotes fading probability over one link, which can be evaluated as:

$$p_f = prob\left(g < \frac{P_{r\min} d^4}{P_{tx}} \right) = 1 - e^{-\frac{P_{r\min} d^4}{P_{tx}}}, \tag{13}$$

where $P_{r\min}$ is the receiver sensitivity, d is the distance between transmitting and receiving nodes, P_{tx} denotes the transmission power and g is the random fading power gain. With flat Rayleigh fading assumption, g is exponential distributed with probability density function (pdf)

$$p_g(x) = \frac{1}{\Omega_g} e^{-\frac{x}{\Omega_g}}, \tag{14}$$

where $\Omega_g = \frac{P_{tx}}{d^4}$ is the average envelope power [35].

For direct transmission scheme, since there is only one link from source to destination, and no intermediate nodes involves in packet transmission, the packet delivery ratio η_d is simply

$$\eta_d = 1 - p_{f_0} = e^{-\frac{P_{r\min} d_{SD}^4}{P_S^{tx}}}, \tag{15}$$

24

where d_{SD} denotes the distance between source and destination, and P_S^{tx} is data transmission power at the source.

For cooperative transmission scheme, the packet transmission operates in two stages: from source to relays and from relays to destination. Hence, the average packet delivery ratio η_c is the multiplication of the packet delivery ratios over these two stages:

$$\eta_c = \eta_{SR} \cdot \eta_{RD}, \tag{16}$$

where η_{SR} denotes the packet delivery ratio from source to selected relays, formulated as

$$\eta_{SR} = 1 - \sum_{i=0}^{J-1} \binom{N}{i} (1 - p_{f_1})^i p_{f_1}^{N-i}, \tag{17}$$

and η_{RD} is the packet delivery ratio from relays to the destination, given by

$$\eta_{RD} = 1 - p_{f_2}^{J}, \tag{18}$$

N denotes number of intermediate nodes between source and destination, J is the prescribed number of cooperative nodes, p_{f_1} and p_{f_2} are the fading probabilities over these two transmission links, which can be evaluated from (13).

IV-2 Energy Consumption Analysis

We next analyze energy consumption per correctly received packet using the parameters in our energy consumption model and the previous derived average packet delivery ratio.

For direct transmission scheme, the energy consumed by successfully transmitting a k-bit packet from source to destination is formulated as

$$E_d = \frac{k\left(e_T^{elec} + \frac{P_S^{tx}}{R_b} + e_R^{elec}\eta_d\right)}{\eta_d}, \tag{19}$$

where e_T^{elec} and e_R^{elec} are the parameters coming from the energy consumption model, which represent energy dissipated to run the transmitter and receiver circuitry, respectively. P_S^{tx} denotes the transmission power at source, R_b is the bit rate, and η_d is the average packet delivery ratio of the direct transmission, as derived in (15).

For cooperative transmission scheme, we first evaluate the energy consumption of transmitting a k-bit packet from the source to the selected relays, i.e.,

$$E_{SR} = k\left(e_T^{elec} + \frac{P_{SR}^{tx}}{R_b} + Je_R^{elec}\eta_{SR} \right), \tag{20}$$

and then we analyze the energy consumption of transmitting one packet from the selected relays to the destination, given by

$$E_{RD} = k\eta_{SR}\left[J\left(e_T^{elec} + \frac{P_{RD}^{tx}}{R_b} \right) + e_R^{elec}\eta_{RD} \right]. \tag{21}$$

Hence, the overall energy consumption per correctly received packet is formulated as

$$E_c = \frac{E_{SR} + E_{RD}}{\eta_c} = \frac{k\left[e_T^{elec}\left(1 + J\eta_{SR}\right) + \frac{P_{SR}^{tx} + JP_{RD}^{tx}\eta_{SR}}{R_b} + e_R^{elec}\eta_{SR}\left(J + \eta_{RD}\right) \right]}{\eta_c}, \tag{22}$$

where P_{SR}^{tx} and P_{RD}^{tx} denote transmission power of sending data packet from source to relays and from relays to destination, respectively. η_{SR} and η_{RD} are the packet delivery ratio over these two links, as derived in (17) and (18), respectively.

The comparison of analytical and simulation results will be addressed in section IV-9.

IV-3 Simulation Model

We assume a minimum-hop (MH) routing path from the data-collecting sensor node to the remote sink is initially established over a few active nodes and the topology over each MH hop is shown in Figure 7. The simulated system uses packets with size 100bits transmitted at a rate of 10kbaud over frequency-flat Rayleigh fading channel using uncoded QPSK. The channel fading gain is randomly generated and invariant during each handshaking sequence (RTS-CTS-DATA-ACK) transmission process.

Since no FEC coding is used, the packet will be received correctly only if all bits in the packet are correct. If each bit inside the packet has the same bit error rate (BER) and bit errors are uncorrelated, the instantaneous packet error rate (PER) can be related to BER through

$$PER = 1 - (1 - BER)^k, \tag{23}$$

where k denotes the packet size. With the noise power to be -128dBm at receiver, a certain level of receiver sensitivity ($P_{r\min}$) is required to guarantee the packet error rate no larger than prescribed target value. The transmission power is adjusted for each data packet over each link with maximum value restricted to 0.5W. Each node is initially supplied with energy of 10J and transmission retry limit is set to be 3. Table 1 lists all the simulation parameters.

Table 1: Simulation parameters

Parameter	Description	Value / Range
R_b	Bit rate	20kbps
B	Baud rate	10kbaud
k	Packet size	100bit
x	Non-negative weighting factor in cost function	30
n	Path loss exponent	4

E	Node's initial energy level	10J
e_T^{elec}	Energy dissipated to run transmitter circuity	50nJ/bit
e_R^{elec}	Energy dissipated to run receiver circuity	50nJ/bit
N	Number of intermediate nodes over one MH hop	5–20
J	Number of cooperative nodes over one MH hop	1–5
d	Distance over one MH hop	5–40m
P_{tmax}	Maximum allowed transmission power at each node	0.5W
P_{rmin}	Receive sensitivity	-105dBm—-70dBm
P_N	Noise power at receiver	1.6×10^{-16} W(-128dBm)
N_0	Single-sided noise spectrum density	8×10^{-21} W/Hz(-171dBm)
$hopno$	Number of MH hops	3, 5
$pktno$	Total number of packets that are sent	100, 200, 300
$retryno$	Maximum allowed retransmission times	1, 3
PER	Receiver target packet error rate	10^{-1}–10^{-4}

IV-4 Comparison of Cooperative and Non-cooperative Schemes

We first conduct simulations to compare our proposed scheme with other cooperative and non-cooperative schemes shown in Table 2.

Table 2: Simulation schemes

Scheme	Description
Cooperative transmission and ARQ retransmission (CoopTx&Retx)	Source → selected relays; selected relays → destination. One intermediate node retransmits packet.
Cooperative relay transmission only (CoopTxOnly)	Source → selected relays; selected relays → destination. Selected relays retransmit packet
Non-cooperative relay transmission (NonCoopTx)	Source → a minimum cost relay; this relay → destination. This relay retransmits packet.
Cooperative retransmission only (RetxCoop)	Source → destination. One intermediate node retransmits packet.
Direct transmission (Direct)	Source → destination. Source retransmits packet.
Mid relay transmission (MidRelay)	A node is deployed on halfway from source to destination to serve as relay.

To evaluate energy efficiency, we first consider the energy consumption per successful packet, which is computed by dividing overall energy expenditure by the total number of packets correctly received at the destination. In simulations, two hundred ($pktno$=200) packets are sent over a three-hop ($hopno$=3) MH route, eight (N=8) intermediate nodes are generated randomly nearby each hop and two (J=2) of them are required to serve as relays. The results are shown in Figure 10. We observe that compared to other cooperative and non-cooperative schemes, significant energy savings can be achieved by our proposed scheme especially when small packet error rate at receiver is required.
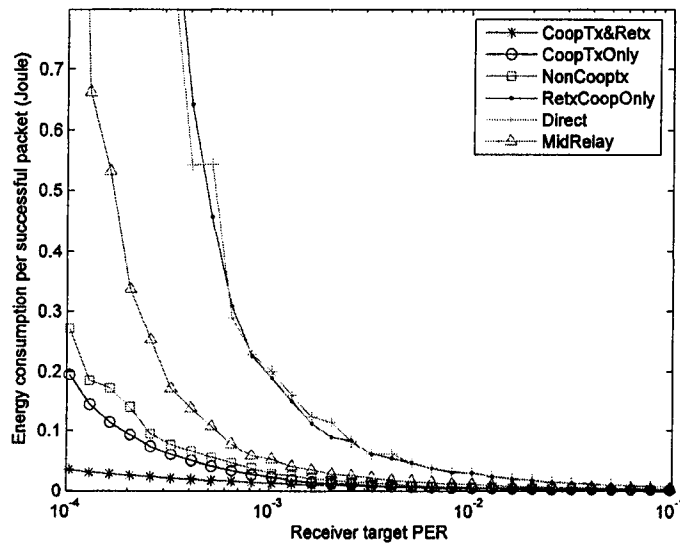
Figure 10: Comparison of different cooperative and non-cooperative schemes ($hopno$=3, $pktno$=200, N=8, J=2, d=20): energy consumption per successful packet vs receiver target PER.

Next, we look at the minimum of all the nodes' residual energy level after sending two hundred packets over a three-hop MH route. Figure 11 presents the results. As can be seen, the proposed scheme achieves highest minimum of nodes' residual energy level, which indicates that overall energy expenditure can be distributed more evenly over multiple nodes to prolong sensor network lifetime.
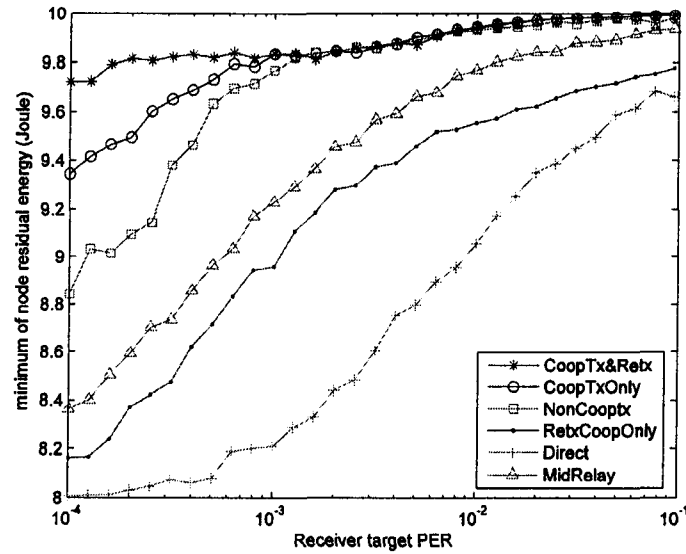
Figure 11: Comparison of different cooperative and non-cooperative schemes (*hopno*=3, *pktno*=200, *N*=8, *J*=2, *d*=20): minimum of node residual energy vs receiver target PER.

To evaluate reliability of packet transmission, we compared the average packet delivery ratio of different schemes. Figure 12 shows that our scheme has the highest average packet delivery ratio.
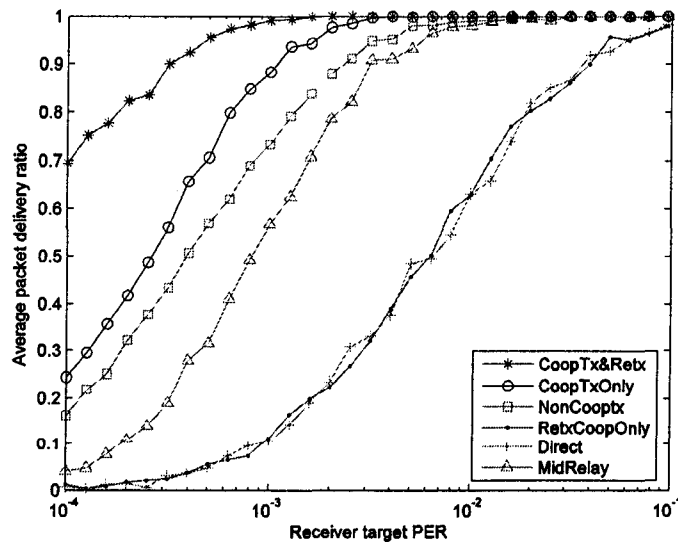

Figure 12: Comparison of different cooperative and non-cooperative schemes (*hopno*=3, *pktno*=200, *N*=8, *J*=2, *d*=20): average packet delivery ratio vs receiver target PER.

IV-5 Extension to Two Next-hop Nodes Scenario

We extended all the schemes (except mid relay scheme) in Table 2 from one to two next-hop node(s) scenario and compared their performance. The two next-hop nodes scenario of our proposed scheme is illustrated in Figure 13. Note that now there are two nodes ($D1$ and $D2$) available to receive the packet transmission from the selected relays. The packet delivery fails only when both $D1$ and $D2$ can not receive the packet correctly. In case that both of them receive packet correctly, the one with larger remaining energy will serve as the destination, i.e., the source of next MH hop path.
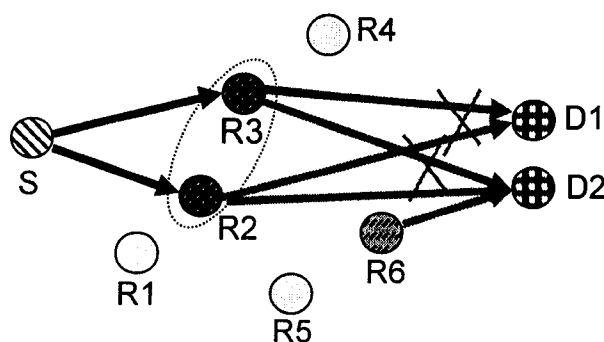

Figure 13: Two next-hop nodes scenario of cooperative transmission over one MH hop.

We conducted simulations to compare the performance of one and two next-hop node(s) scenario where three hundred ($pktno$=300) packets are sent over a three-hop ($hopno$=3) MH path and two (J=2) out of eight (N=8) intermediate nodes are selected as cooperative relays. Results are shown in Figures 14-16. Figure 14 compares energy consumption per successfully received packet of different schemes under one and two next-hop nodes scenarios. Figure 15 and Figure 16 compare the minimum of nodes' residual energy and the average packet delivery ratio, respectively. It is observed that the performance improvement of using two next-hop nodes is more evident for non-cooperative schemes than the cooperative schemes. This is because using two next-hop

nodes provides receiver diversity, hence, improving the performance. Since our cooperative relay scheme has explored spatial diversity to a good extent, additional diversity gain from two next-hop nodes only improves the performance slightly.

Figure 14: Comparison of one and two next-hop node(s) scenarios of different cooperative and non cooperative schemes (*hopno*=3, *pktno*=300, *N*=8, *J*=2, *d*=20): energy consumption per successful packet vs receiver target PER.

Figure 15: Comparison of one and two next-hop node(s) scenarios of different cooperative and non cooperative schemes (*hopno*=3, *pktno*=300, *N*=8, *J*=2, *d*=20): minimum of node residual energy vs receiver target PER.
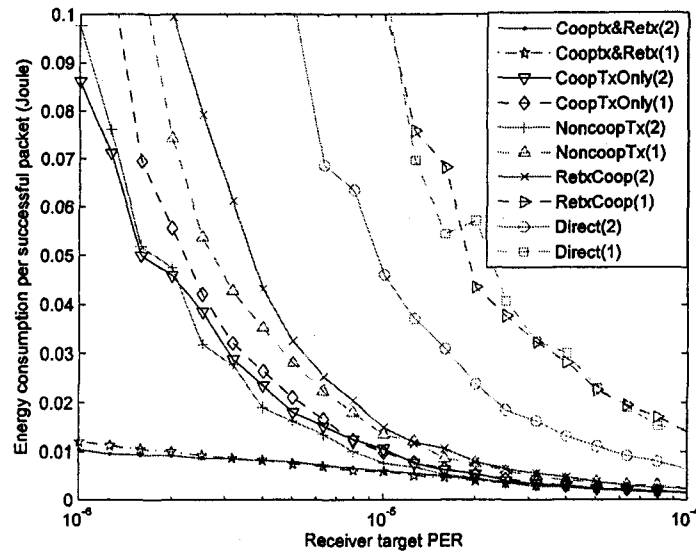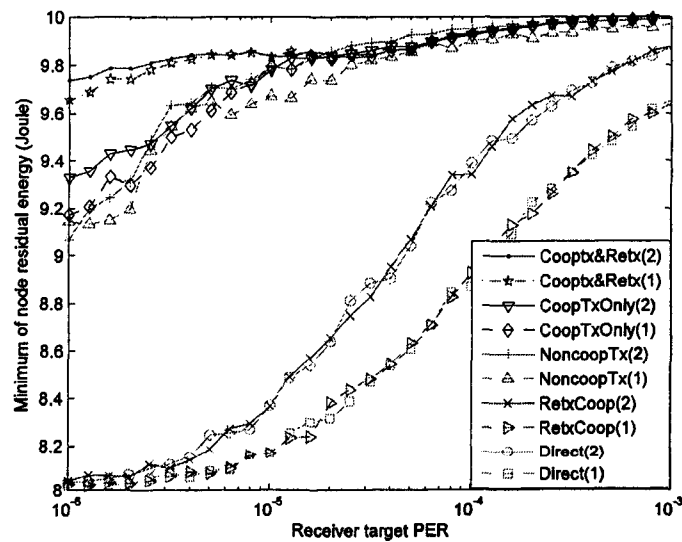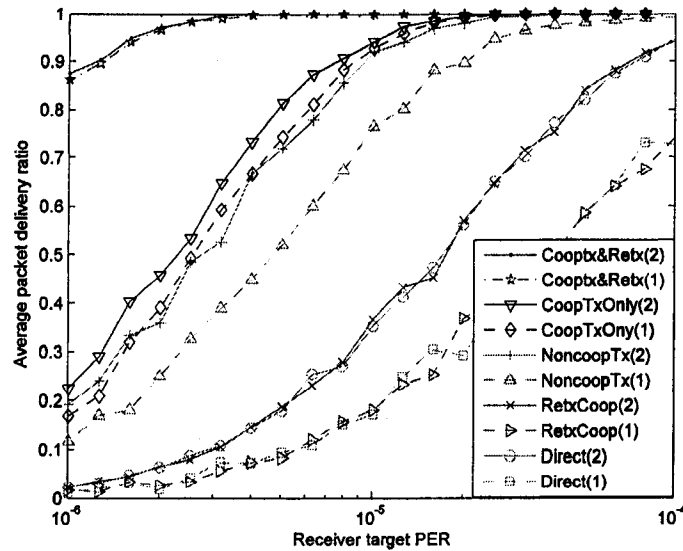
Figure 16: Comparison of one and two next-hop node(s) scenarios of different cooperative and non cooperative schemes (*hopno*=3, *pktno*=300, *N*=8, *J*=2, *d*=20): average packet delivery ratio vs receiver target PER.

IV-6 Effect of Number of Cooperative relays and TPC

Since node cooperation and transmission power control play important roles to enhance energy efficiency and transmission reliability in our proposed scheme, it is worthwhile to investigate the effect of number of cooperative relays (denoted by *J*) and the influence of transmission power control. Three transmission power cases are examined and compared in our simulations.

- Ideal TPC: transmission power adjustment is based on both link distance and channel state information.

- Non Ideal TPC: transmission power adjustment is based on link distance only.

- No TPC: data packet is transmitted at maximum power level.

In simulations, we fixed receiver sensitivity at certain moderate value (-84dBm) and varied number of cooperative relays (*J*) from 1 to 5. Note that *J*=1 represents non-cooperative relay scheme. The performances of ideal, non ideal and no TPC cases are

compared in Figures 17-19, where energy consumption per successful packet is shown in Figure 17, Figure 18 shows the minimum of nodes' residual energy and Figure 19 plots the average packet delivery ratio.

As can be seen from Figure 17, considerable energy savings can be achieved when J goes from 1 to 2, showing the benefits of node cooperation. After that when J increases from 2 to 5, for the two variable transmission power cases (Ideal TPC and Non Ideal TPC) , the energy savings become small while for the fixed transmission power case (No TPC), the energy consumption increases. This is because when more nodes are involved in cooperation, the overall transmission energy consumption can be reduced due to the increased spatial diversity gains, but the overall reception energy consumption will also increase. Similar observation is obtained regarding the minimum of nodes' residual energy (Figure 18). Generally, in terms of energy efficiency, No TPC performs worse than Ideal TPC and Non Ideal TPC.

In terms of average delivery ratio (Figure 19), again, performance improves when J goes from 1 to 2. However, this time, No TPC performs better than Non Ideal TPC. This is because, in No TPC case, each data packet is transmitted at the maximum power level, while in Non Ideal TPC case, the data transmission power is adjusted based on the link distance, hence, it becomes smaller, while in both cases channel is unknown.

Figure 17: Comparison of cooperative scheme with Ideal, Non Ideal and No TPC (*hopno*=3, *pktno*=100, *N*=20, *Prmin*=-84dBm, *d*=20): energy consumption per successful packet vs number of cooperative relays *J*.

Figure 18: Comparison of cooperative scheme with Ideal, Non Ideal and No TPC (*hopno*=3, *pktno*=100, *N*=20, *Prmin*=-84dBm, *d*=20): minimum of relay node residuale energy vs number of cooperative relays *J*.
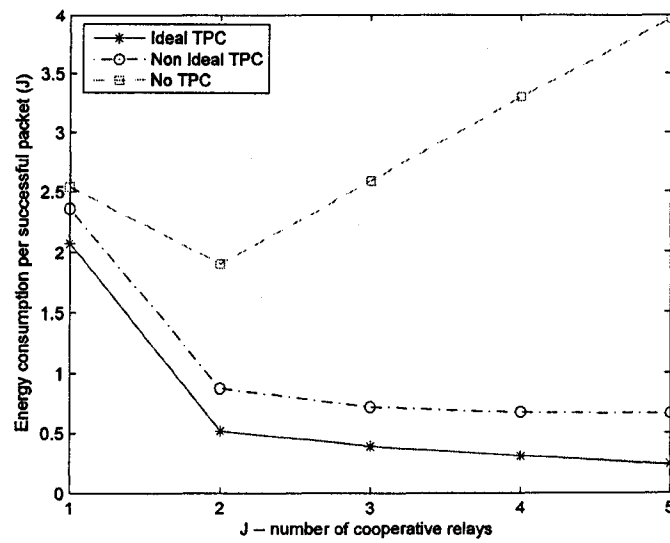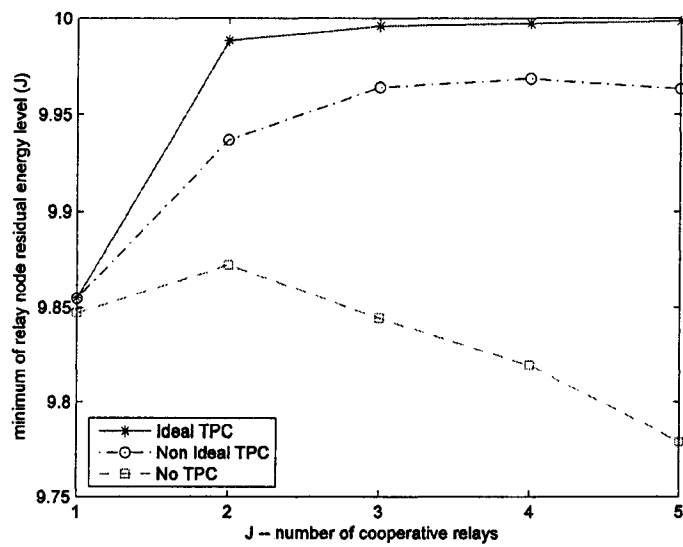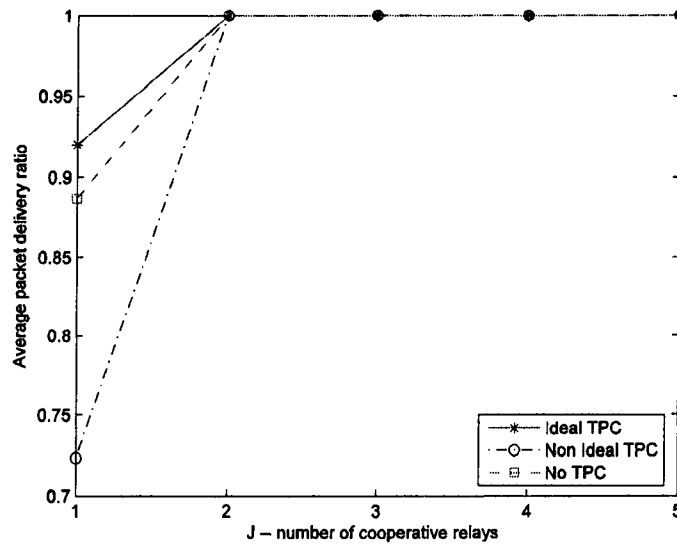
Figure 19: Comparison of cooperative scheme with Ideal, Non Ideal and No TPC (*hopno*=3, *pktno*=100, *N*=20, *Prmin*=-84dBm, *d*=20): (c) average packet delivery ratio vs number of cooperative relays *J*.

To further investigate the effect of number of cooperative relays and power control, we compared the performance of different *J* (from 1 to 5) varying the receiver sensitivity. The number of intermediate nodes *N* is fixed at twenty (*N*=20) and one hundred packets are sent over a three-hop MH route. The results of energy consumption, minimum of nodes' residual energy under three transmission power cases are shown in Figures 20-22 and Figures 23-25, respectively.

Figure 20: Comparison of cooperative scheme with different number of cooperative relays (*J*) under Ideal TPC case (*hopno*=3, *pktno*=100, *N*=20, *d*=20): energy consumption per successful packet vs receiver sensitivity.

Figure 21: Comparison of cooperative scheme with different number of cooperative relays (*J*) under Non Ideal TPC case (*hopno*=3, *pktno*=100, *N*=20, *d*=20): energy consumption per successful packet vs receiver sensitivity.

Figure 22: Comparison of cooperative scheme with different number of cooperative relays (J) under No TPC case (*hopno*=3, *pktno*=100, N=20, d=20): energy consumption per successful packet vs receiver sensitivity.

Figure 23: Comparison of cooperative scheme with different number of cooperative relays (J) under Ideal TPC case (*hopno*=3, *pktno*=100, N=20, d=20): minimum of node residual energy vs. receiver sensitivity.
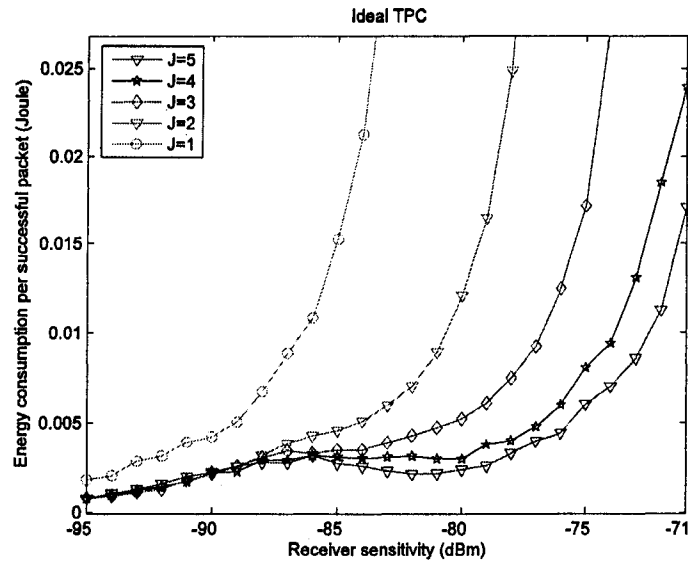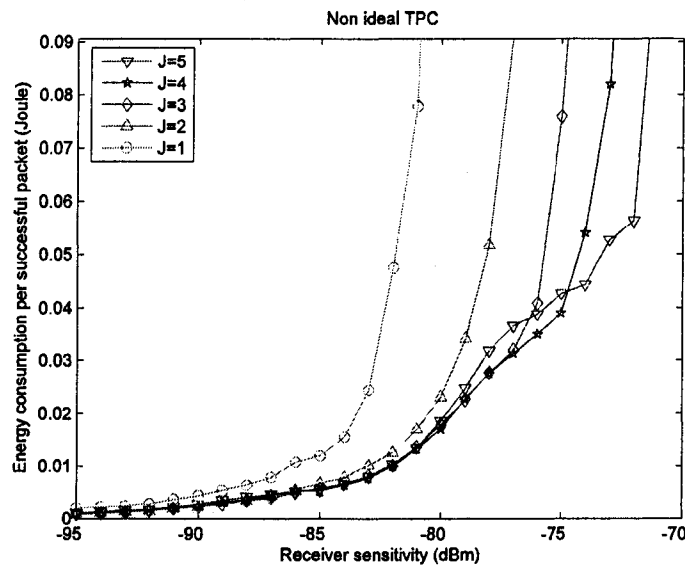
Figure 24: Comparison of cooperative scheme with different number of cooperative relays (*J*) under Non Ideal TPC case (*hopno*=3, *pktno*=100, *N*=20, *d*=20): minimum of node residual energy vs. receiver sensitivity.

Figure 25: Comparison of cooperative scheme with different number of cooperative relays (*J*) under No TPC case (*hopno*=3, *pktno*=100, *N*=20, *d*=20): minimum of node residual energy vs. receiver sensitivity.

As observed from Figures 20-25, when receiver sensitivity is good (small value), cooperative relay scheme (*J* >1) improves performance under both Ideal and Non Ideal TPC cases, but it has no advantages when more than two relays are involved in cooperation. In no TPC case with good receiver sensitivity, non-cooperative scheme is

more energy-efficient. On the other hand, when receiver sensitivity gets poor, the benefits

of node cooperation grow up for all three transmission power cases, and more nodes
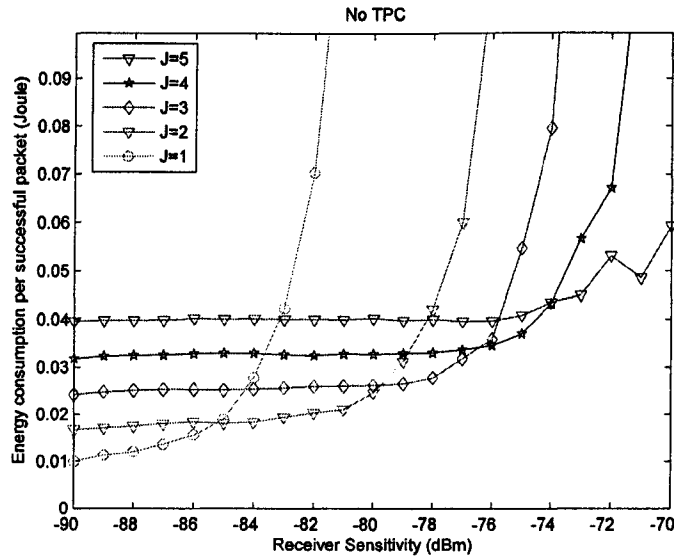
involved, better performance can be achieved.

Figure 26: Comparison of cooperative scheme with different number of cooperative relays (*J*) under Ideal TPC case (*hopno*=3, *pktno*=100, *N*=20, *d*=20): average packet delivery ratio vs. receiver sensitivity.
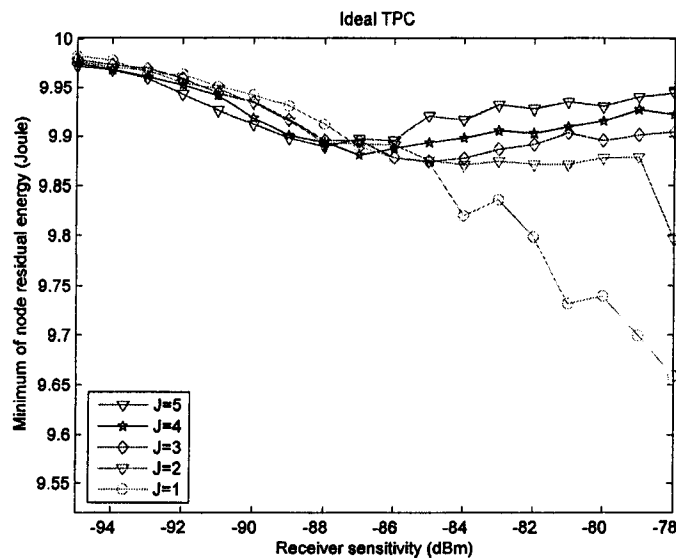

Figure 27: Comparison of cooperative scheme with different number of cooperative relays (*J*) under Non Ideal TPC case (*hopno*=3, *pktno*=100, *N*=20, *d*=20): average packet delivery ratio vs. receiver sensitivity.
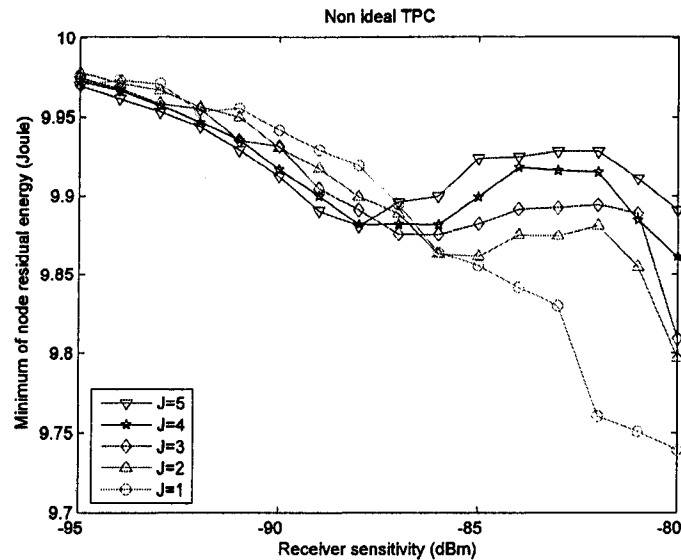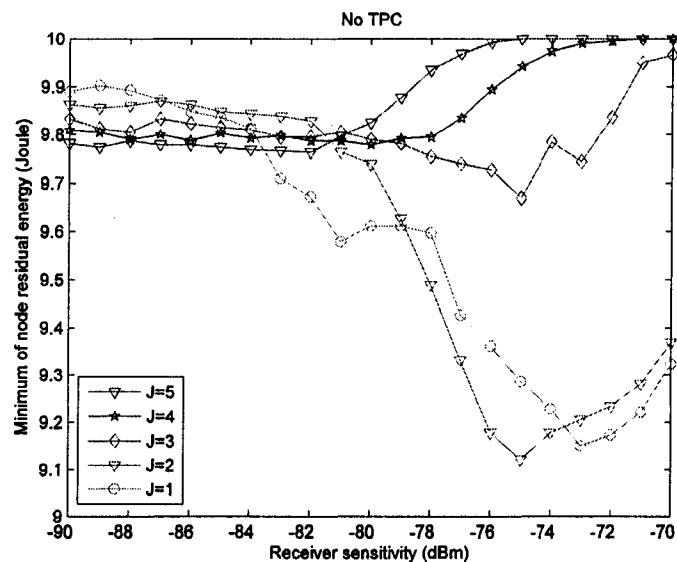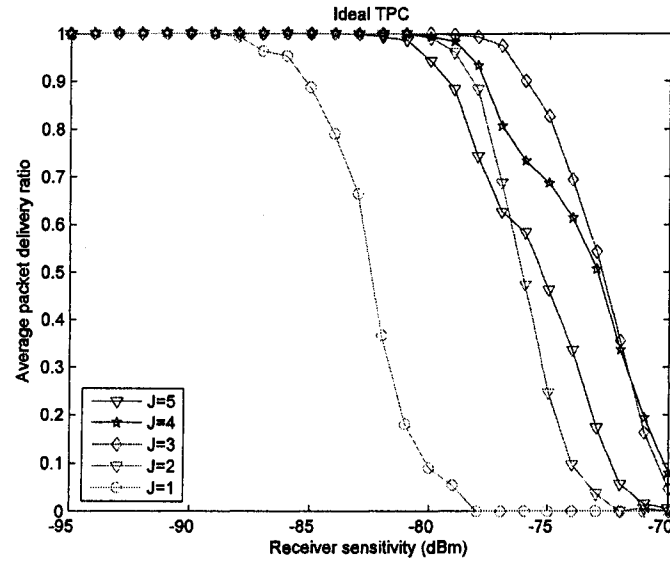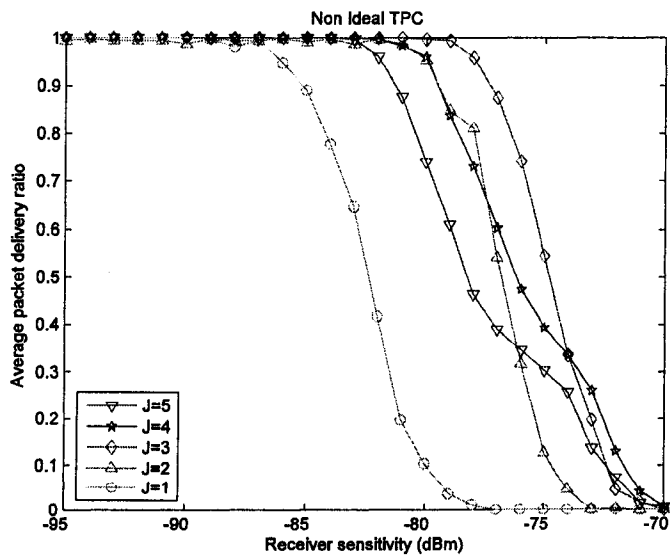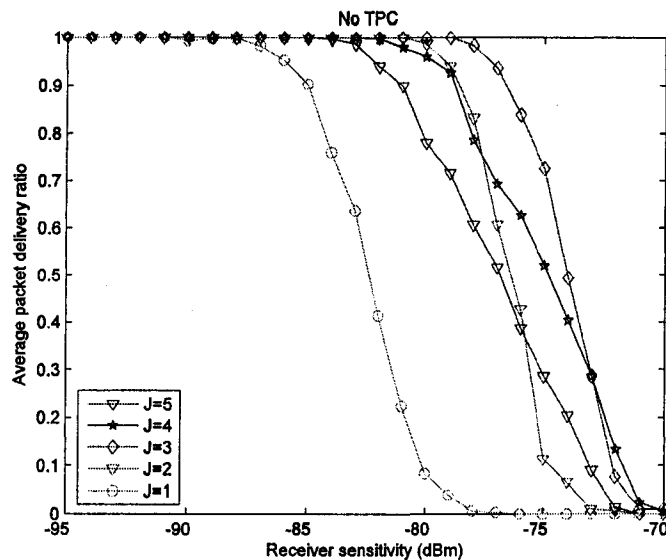
Figure 28: Comparison of cooperative scheme with different number of cooperative relays (*J*) under No TPC case (*hopno*=3, *pktno*=100, *N*=20, *d*=20): average packet delivery ratio vs. receiver sensitivity.

We then examine the performance of average packet delivery ratio under different transmission power cases, shown in Figures 26-28. Again, we observe that packet delivery ratio increases considerably when *J* goes from 1 to 2, due to the benefits of node cooperation. However, when *J* increases from 2 to 5, the performance of large *J* is not always better than that of small *J*. Instead, at poor receiver sensitivity level (larger than -80dBm), packet delivery ratio improves first then drops for all three transmission power cases (e.g. *J*=3 performs better than *J*=2, 4, 5). When receiver sensitivity gets worse (larger than -75dBm), the performance of large *J* starts improving (*J* = 5 is now better than *J*=2). This phenomena can be explained by relay selection process, where *J* out of *N* number of intermediate nodes has to be selected as relays, i.e., all of them must be able to receive data packet correctly, otherwise, the packet delivery fails. With fixed number of intermediate nodes (*N*) and unpredictable fading environment, it is likely packet delivery ratio drops at large value of *J*. To confirm it, we conducted simulation with ten intermediate nodes (*N*=10), and obtained similar but more evident results.

IV-7 Effect of Number of Intermediate Nodes

To evaluate effect of number of intermediate nodes (N), we conducted simulations with fixed two number of cooperative relays ($J=2$) and compared performance of different N ($N=5$, 10, 15 and 20) varying the receiver sensitivity. The results of energy consumption per successful packet, minimum of relay node residual energy and average packet delivery ratio, are shown in Figures 29-31, respectively.
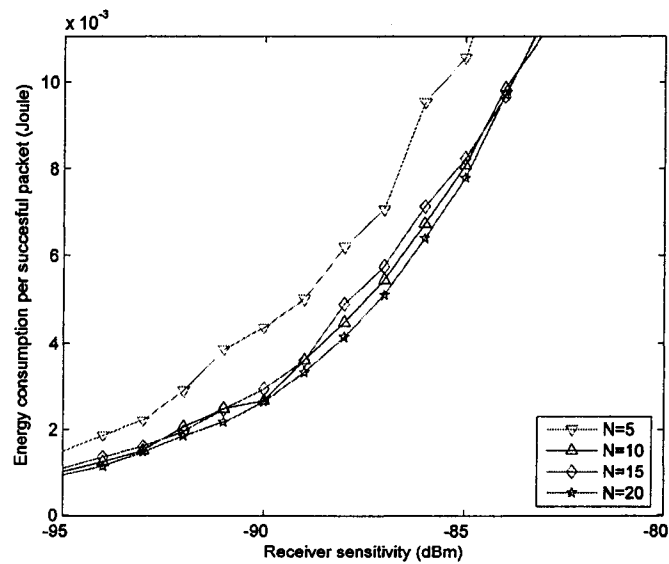
Figure 29: Comparison of cooperative scheme with different number of intermediate nodes (N) (*hopno*=3, *pktno*=100, $J=2$, $d=20$): energy consumption per successful packet vs receiver sensitivity.
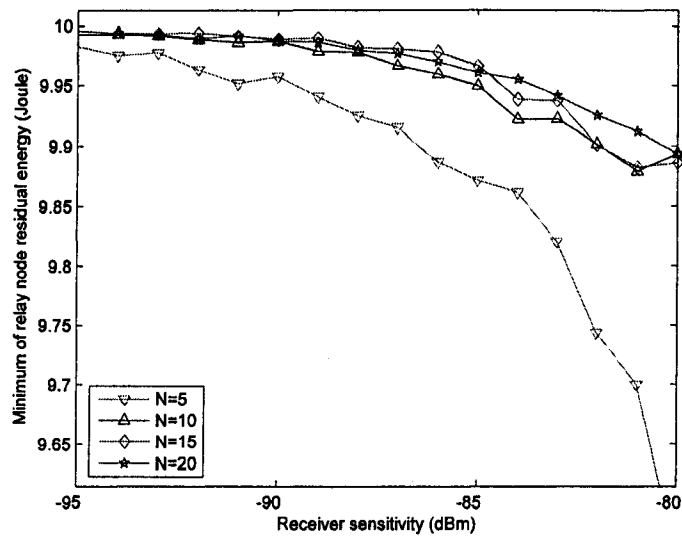
Figure 30: Comparison of cooperative scheme with different number of intermediate nodes (*N*) (*hopno*=3, *pktno*=100, *J*=2, *d*=20): minimum of relay node residual energy vs receiver sensitivity.
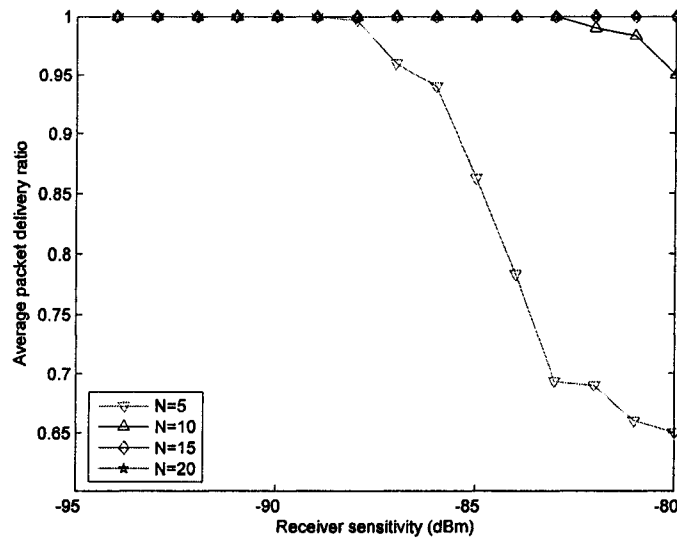
Figure 31: Comparison of cooperative scheme with different number of intermediate nodes (*N*) (*hopno*=3, *pktno*=100, *J*=2, *d*=20): average packet delivery ratio vs receiver sensitivity.

From Figure 29, we observe that energy savings is evident when *N* goes from 5 to 10, however, when *N* is from 10 to 15 and 20, the energy savings is small. This is intuitive since large *N* means more nodes turn active and are available to be chosen as relays, for only two cooperating relays needed, too many nodes available is not

necessary. Similar trends are observed in terms of minimum of nodes residual energy and average packet delivery ratio.

IV-8 Effect of CSI and Transmission Distance

In our scheme, channel state information (CSI) in the physical layer is explored over each link and utilized in relay selection process and transmission power control. Figures 32-33 compares energy efficiency with and without instantaneous CSI. We observe that the energy savings achieved by cooperative scheme with CSI is more pronounced than the scheme without CSI especially at small packet error rate requirement.
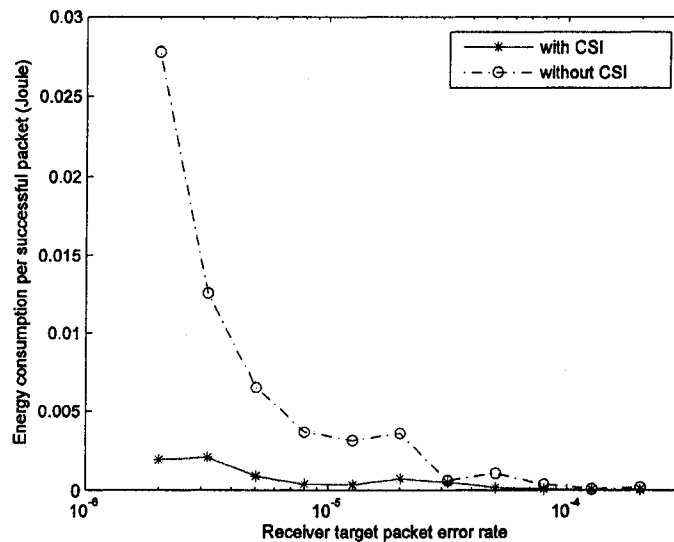
Figure 32: Comparison of cooperative scheme with and without channel state information (CSI) (*hopno*=3, *pktno*=20, *N*=8, *J*=2, *d*=20): energy consumption per successful packet vs receiver target PER.
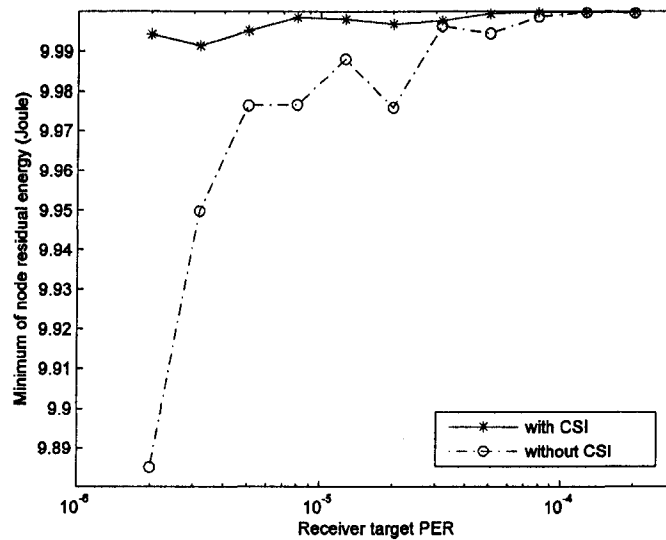
Figure 33: Comparison of cooperative scheme with and without channel state information (CSI) (*hopno*=3, *pktno*=20, *N*=8, *J*=2, *d*=20): minimum of node residual energy vs receiver target PER.

We further examine the effect of transmission distance on the energy efficiency. We ran simulations where two hundred packets are sent over a five-hop MH route, and over each hop two out of eight nodes are required to serve as cooperative relays. We varied transmission distance per hop from 5m to 40m while fixing the receiver sensitivity at -94dBm to compare the energy consumption and the minimum of node residual energy of different cooperative and non-cooperative schemes in Table 2. The results are shown in Figures 34-35. As expected, more energy is consumed when transmitting at longer distance and for long range transmissions, the proposed scheme gains more advantages.
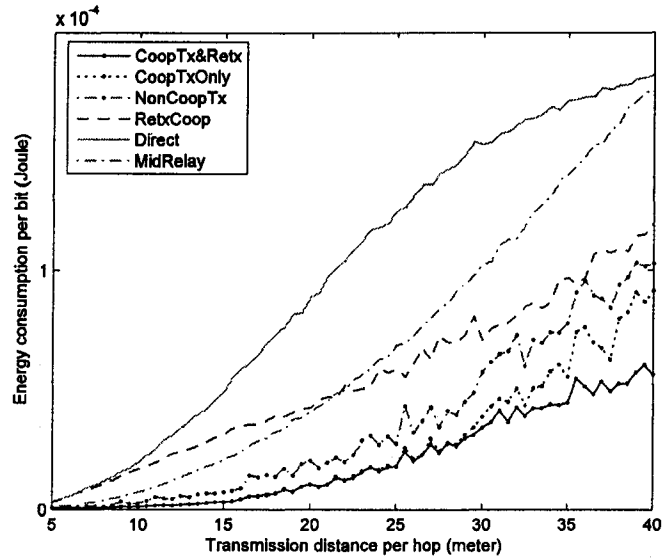
Figure 34: Impact of transmission distance on different cooperative and non-cooperative schemes (*hopno*=5, *pktno*=200, *N*=8, *J*=2, *Prmin*=-94dBm): energy consumption per bit vs transmission distance per hop.
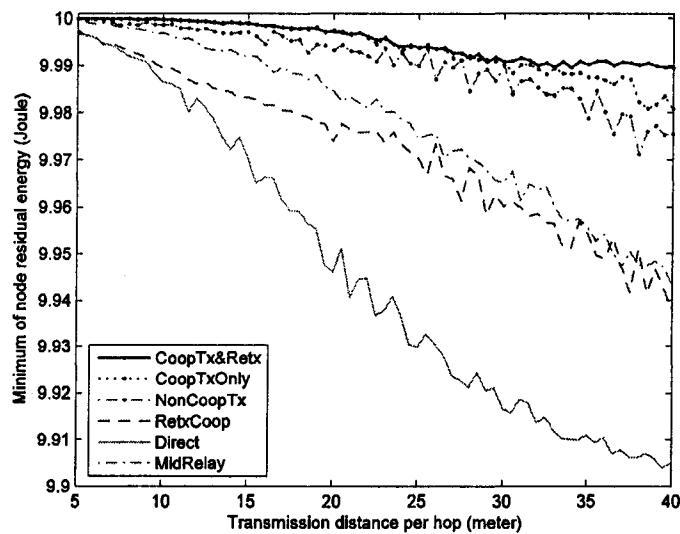
Figure 35: Impact of transmission distance on different cooperative and non-cooperative schemes (*hopno*=5, *pktno*=200, *N*=8, *J*=2, *Prmin*=-94dBm): minimum of node residual energy vs. transmission distance per hop.

IV-9 Comparison of Theoretical and Simulation Results

We analyzed average packet delivery ratio and energy consumption in section IV-1 and IV-2, respectively. The analytical results are derived in equations (15) to (22). In order to compare the theoretical analysis and simulation results, we set distance between

source and destination to be 20m and the distances from source to relays and from relays to destination to be 10m and 12.7m, respectively. Ten intermediate nodes (N=10) are generated randomly over each MH hop and J of them are selected as cooperative relays. The packet retry limit is set to 1. We compared theoretical and simulation results of relay scheme for J from 1 to 5 and the direct transmission scheme (J=0). Figures 36 shows the results of average packet delivery ratio and Figure 37 shows the energy consumption per successful packet. We observe a good agreement between theoretical analysis and simulation results in both average packet delivery ratio and effective packet energy consumption for all the comparison schemes.
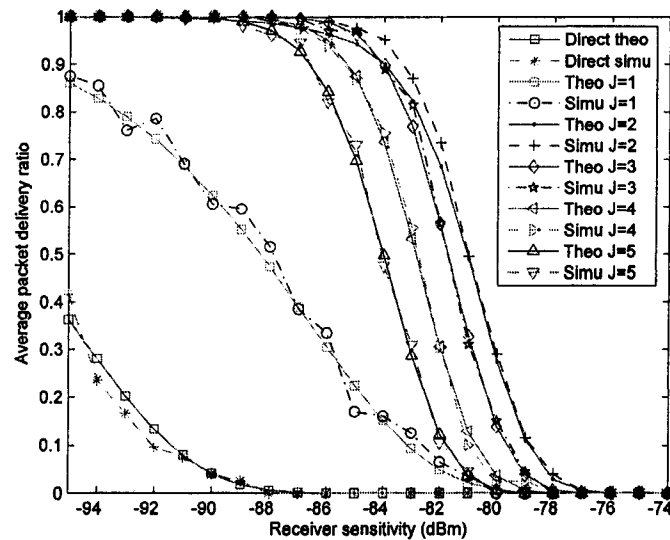
Figure 36: Comparison of theoretical and simulation results for direct, non-cooperative (J=1) and cooperative (J from 2 to 5) schemes (*hopno*=1, *pktno*=200, N=10, *retryno*=1, d=20): energy consumption per successful packet vs receiver sensitivity.
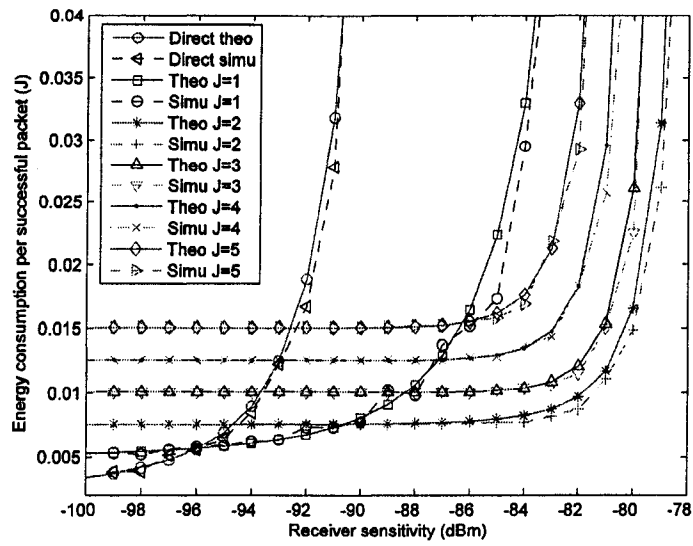
(37)

Figure 37: Comparison of theoretical and simulation results for direct, non-cooperative (J=1) and cooperative (J from 2 to 5) schemes ($hopno$=1, $pktno$=200, N=10, $retryno$=1, d=20): average packet delivery ratio vs receiver sensitivity.

CHAPTER V

CONCLUSIONS

V-1 Summary of Contributions

We have proposed a cooperative transmission scheme, denoted cooperative transmission and ARQ retransmission, for multihop communications in wireless sensor networks. The scheme uses relay nodes in conjunction with transmission power control and cooperative ARQ to improve energy efficiency and transmission reliability of packet delivery in the presence of fading.

The cooperative transmission scheme consists of relay selection followed by cooperative data transmission. The cost function is evaluated in relay selection process and it reflects both node's residual energy level as well as energy consumed during packet transmission and reception. Transmission power control is employed over each link for each data packet transmission and is accomplished by using MAC layer RTS-CTS handshaking messages with limited overhead. Channel information is explored in relay selection process and utilized in transmission power adjustment. Moreover, a cooperative ARQ is incorporated, where an intermediate node is selected to help packet retransmission.

We performed theoretical analysis of average packet delivery ratio and energy consumption of cooperative relay scheme and compared to the simulation results. A good agreement is observed between analytical and simulation results.

In simulations, we first compared our proposed scheme with other five cooperative and non-cooperative schemes. The results show that the proposed

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cooperative relay scheme improves energy efficiency, reliable packet delivery ratio and extends nodes battery lifetime.

Then, we extended all the six simulation schemes from one to two next-hop node(s) scenario and compared their performance. The results show that the benefits of using two next-hop nodes are more evident for non-cooperative schemes than for cooperative schemes and using two next-hop nodes only improves the performance of our cooperative relay scheme slightly.

Next, we examined the effects of various factors on system performance including number of cooperative relays (J), transmission power control (TPC), number of intermediate nodes (N), channel state information (CSI) and transmission distance. The simulation-based studies are summarized as follows:

- Increasing number of cooperative relay nodes gains more advantages in energy efficiency when receiver sensitivity is poor. In case of good receiver sensitivity and fixed maximum transmission power scenario (No TPC), non-cooperative relay scheme performs better.

- More nodes involved in cooperation do not monotonically results in the increased packet delivery ratio. Instead, the average packet delivery ratio increases first then drops due to the relay selection process.

- Cooperative relaying with ideal TPC performs best in both energy efficiency and average packet delivery ratio while an energy and packet delivery ratio trade-off is observed between non ideal TPC and no TPC cases.

- Increasing number of intermediate nodes improves performance but return diminishes when it is considerably larger than number of cooperative relays .

- Energy savings achieved by our cooperative scheme with CSI is more pronounced than that without CSI especially when small receiver packet error rate is required.

- The proposed scheme has more advantages for long range transmission.

V-2 Future Work

The improved energy efficiency and packet delivery ratio of our cooperative scheme comes at the price of more transmission time due to the increased number of hops and additional processing in relay selection and transmission power control. It is interesting to investigate energy-delay trade-off and additional cost from TPC. Another interesting issue is the optimization of number of cooperative nodes to maximize both packet delivery ratio and energy efficiency when perfect channel state information is unavailable. In this work, the proposed scheme is applied over the MH routing path. Incorporating node cooperation with other popular routing protocols, such as DSR, AODV etc., is also worth pursuing. We leave these problems for the future research.

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