A Study of Energy-efficient Routing Supporting Coordinated Sleep Scheduling in Wireless Ad Hoc Networks

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

A wireless ad hoc network is a collection of wireless computing devices that self-configure to form a network independently of any fixed infrastructure. Many wireless ad hoc network devices such as smartphones and tablets are usually powered by batteries with a limited operation time. This poses a significant challenge to the design of low-power network protocols. On one hand, energy-efficient routing protocols are widely discussed to reduce the end-to-end transmission energy by controlling the transmission power at senders. Recently, opportunistic routing (OR) has attracted a lot of attention for maximizing energy efficiency by exploiting the gains of multi-receiver diversity. On the other hand, sleep scheduling is commonly adopted as an effective mechanism to further reduce power wasted in overhearing and idle listening. However, the prior work has mainly treated energy-efficient routing and sleep scheduling as two separate tasks, which leads to a serious problem that neither component can fully minimize the network-wide energy consumption. In this thesis, we study how energy-efficient routing can be coordinated with sleep scheduling to increase network-side energy efficiency. We identify a trade-off between the decreased transmit power at senders due to multi-receiver diversity and the increased power at forwarders with the incorporation of coordinated sleep scheduling. Moreover, we provide a comprehensive evaluation of coordinated sleep scheduling impact on energy-efficient routing performance based on a 2-D grid topology and time division multiple access (TDMA) medium access control (MAC). Extensive simulation results demonstrate the effectiveness of the integrated function of coordinated sleep scheduling, significant impact of coordinated sleep scheduling on the energy-efficient routing performance and relationship between the network conditions (in terms of the traffic load and node density) and overall system performance achieved by different energy-efficient routing protocols.

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List of Abbreviations

AC acknowledgement coordination. 16–18, 23, 34, 37, 60

ACK acknowledgement. 10, 11, 13, 17, 18, 27, 33–35, 49

ATIM ad hoc traffic indication message. 10, 11

BPR best path routing. 6–8, 16, 18, 20, 21, 25, 30, 32, 33, 37, 49, 57, 59

BPSK binary phase shift keying. 42, 43

CC convolutional code. 42

CMER comprehensive minimum energy routing. 16, 23

CPU central processing unit. 1

CSMA carrier sense multiple access. 16, 23, 67

CTS clear-to-send. 21

DCF distributed coordination function. 21, 23

DSDV destination sequenced distance vector routing. 40

EAX expected anypath transmissions. 20, 23

EEOR energy-efficient opportunistic routing. 21, 23, 32, 36, 37, 40, 41, 46, 52–57, 59–64, 67, 68, 70

EER end-to-end retransmission. 15, 16, 23

ETX expected transmission numbers. 20, 21, 23

ExOR extremely opportunistic routing. 19, 21, 23

FEC forward error correction. 28, 42

FI final indication. 18, 34, 35, 49

GeRAF geographic random forwarding. 18, 19, 23

GPS global position system. 13, 25

HHR hop-by-hop retransmission. 15, 16, 23, 27, 42, 49

IEEE institute of electrical and electronics engineers. 10, 11, 16, 20, 28, 42, 44

IP internet protocol. 14

LCAR least cost anypath routing. 20, 21, 23

LCD liquid crystal display. 1

LNA low noise amplifier. 47

MAC medium access control. iii, vi, ix, 4, 6, 16, 17, 20, 21, 23, 25, 26, 28, 31, 32, 39, 49, 67

MACA multiple access with collision avoidance. 16

MANET mobile ad hoc network. 3

MECN minimum energy communication network. 13, 23

MHR minimum hop routing. 12, 23, 32, 35, 40, 52–55, 59, 61–64, 67

ML maximum likelihood. 28, 44

MTRTP minimum total reliable transmission power. 15, 23

MTS multicast RTS. 21

MTTP minimum total transmission power. 12, 13, 23

OR opportunistic routing. iii, 6–8, 16, 18–21, 25, 30, 32–34, 41, 49, 54, 56, 57, 59, 62, 64

PAMAS multi-access protocol with signaling. 12, 13, 23

PARO power-aware routing. 13, 23

PDF probability density function. 29

PDP packet delivery probability. 40, 52, 53, 55, 58–61

PEER progressive energy-efficient routing. 14, 23

PER packet error probability. 25, 35, 36, 43, 44, 46, 48, 50, 51, 53

PHY physical layer. 49

PSM power saving mode. 10, 11

QAM quadrature amplitude modulation. 42, 43

QoS quality of service. 66

QPSK quadrature phase shift keying. 42, 43

RMER reliable minimum energy routing. 15, 23, 32, 36, 40, 41, 46, 51, 53–55, 57–59, 61, 62, 64, 67, 69

RTS request-to-send. 9, 21, 33, 35, 49

SINR signal to interference plus noise ratio. 26, 27, 43–46, 48

SISO single-input single-output. 28, 42

SNR signal to noise ratio. 29, 43, 44

TDMA time division multiple access. iii, vi, ix, 4, 17, 18, 21, 25–28, 34, 44, 45, 48, 60, 67

VANET vehicular ad hoc network. 3

WBA wireless broadcast advantage. 6, 19, 52

WLAN wireless local area network. 2

WMN wireless mesh network. 3, 19

WSN wireless sensor network. 3, 10, 19, 23

Chapter 1

Introduction

Recent advances in communication and networking technologies are rapidly making ubiquitous network connectivity a reality. Wireless networks are indispensable for supporting such access anywhere and anytime. Wireless ad hoc networks are being developed in order to solve the problem caused by the deployment where there is no infrastructure or the local infrastructure is not reliable. However, wireless devices have a maximum utility limit when they can be used. One of the greatest limitations is the finite power supplies at small-sized wireless devices, such as sensors, smartphones and laptops. Studies show that the significant power consumers in a typical laptop are the liquid crystal display (LCD) (36%), central processing unit (CPU)/memory (21%), wireless network interface card (18%) and hard drive (18%) [1]. Since the wireless interface is a major source of power consumption when the screen is off, considerable research has been devoted to the low-power design of the entire network protocol stack of wireless ad hoc networks. This chapter presents an overview of the main techniques used as an effort to enhance energy efficiency and discusses motivations and objectives of our study in this thesis.

1.1 Wireless Ad Hoc Networks

Unlike wired networks or cellular networks, a wireless ad hoc network has no fixed networking infrastructure. The basic components of the wireless ad hoc networks architecture are nodes with the capability of wireless communications. As shown in Fig. 1.1, a wireless ad hoc network is a collection of multiple nodes that maintain the network connectivity through wireless communications [2]. In wireless ad hoc networks, each node may communicate directly to others. Due to the limited transmission range of radio, pairs of nodes that are not directly connected need intermediate nodes to forward their traffic. Every intermediate node acts as a router to forward packets for other nodes in the case of multi-hop connections.

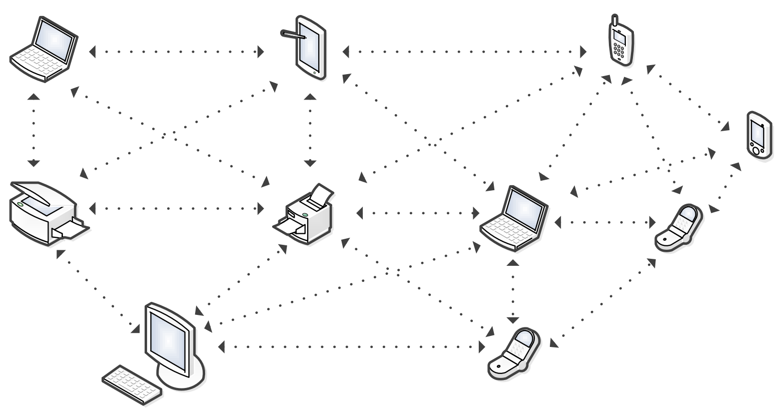

Figure 1.1: An illustration of wireless ad hoc network architecture.

Compared with traditional infrastructure-based wireless networks, such as cellular networks and wireless local area network (WLAN), the main advantages of wireless ad hoc networks are flexibility, low cost and robustness. These characteristics of ad hoc networks initiate a variety of applications and systems. Initially, wireless ad hoc networks were mainly studies in the realm of military or disaster relief situation. More recently, wireless ad hoc networks have also been envisioned for commercial application such as providing Internet connectivity for nodes that are not in the transmission range of a wireless access point. Generally, the field of wireless ad hoc network contains several subfields including mobile ad hoc network (MANET) such as in military communications where all nodes are assumed to be mobile, wireless mesh network (WMN), a combination of ad-hoc and infrastructure network, wireless sensor network (WSN) made up of sensor nodes for monitoring and tracking, and vehicular ad hoc network (VANET) specially for vehicle communications [2].

1.2 Energy-efficient Wireless Ad Hoc Networking

Wireless ad hoc networks normally consist of computing devices powered by battery. Thus, the design of an energy-constrained wireless ad hoc network poses a critical challenge related to the energy budget. The ongoing research is mainly concentrated on solutions that use the minimum possible energy during communications, thereby prolonging the device operation lifetime. In this thesis, we focus on two separate but equally important fronts of power-saving mechanisms: sleep scheduling in the link layer and energy-efficient routing in the network layer. In the following, we first provide the power consumption analysis of the wireless interface at a node, and then introduce two basic techniques and analyze their offered benefits of energy savings.

1.2.1 Power Consumption Analysis

Normally, the wireless interface hardware at a node can operate in any of four different modes: (1).*Transmit mode* when a node transmits a packet; (2).*Receive mode* when a node receives a packet; (3).*Idle mode* when a node is not transmitting or receiving a packet. This mode consumes power because the wireless interface must be up and ready to receive any possible traffic; (4).*Sleep mode* when a node powers off the wireless interface hardware and therefore it can neither transmit nor receive packets. Measurement results have shown that the wireless interface consumes the highest power in the transmit mode and very little power in the sleep mode. The power consumed in the idle mode is however comparable with the power required for the receive mode [3]. For instance, Cisco Aironet Wireless

CardBus Adapter typically consumes 1.78W, 1.08W, 0.67W and 0.02W in the above four modes respectively [4].

For wireless ad hoc networks, there are mainly three sources of non-essential energy expenditure [5]. The first source of energy waste is collisions as a result of random access. In shared-medium wireless networks, there is a high opportunity for packet transmission collisions to occur. When a transmitted packet is corrupted due to collisions, it has to be discarded and retransmissions of the packet cause extra energy. One fundamental target of the MAC protocols is to avoid collisions from interfering nodes. TDMA MAC has the natural advantage of energy saving compared with the contention-based protocols by eliminating collisions. The second source is referred to as idle listening, which corresponds to the energy consumed in the idle mode. When the total traffic load over the network is relatively low, nodes are assumed to be operated in the idle mode for a long time. For instance, most sensor networks generating very light traffic are designed to operate for a long time. Thus, idle listening is a dominant factor of energy waste in such cases. The third source of energy waste is overhearing, during which nodes receives control or data packets that were not transmitted to them. Unfortunately, in a wireless ad hoc network, it is frequently the case that a packet transmission from one node to another will be overheard by all the neighbors of the transmitter. These nodes will consume power needlessly even though the packet is not directed to them. The reason is that the wireless interface does not have any mechanism to not receive that packet. Note that energy consumed by overhearing is the same as that in reception. It is hence a significant waste of energy, especially when node density is high and traffic load is heavy [6].

1.2.2 Sleep Scheduling in the Link Layer

According to the power consumption analysis at a wireless node, powering off the wireless interface can greatly reduce the energy consumed by idle listening and overhearing. Consequently, sleep scheduling (also called duty-cycling) is commonly adopted as a link-layer power-saving mechanism in the wireless ad hoc networks. This mechanism allows nodes to enter the low-power sleep mode by turning off the wireless interface whenever there is no communication demand. By doing this, the channel time is divided into sleep periods and active periods, as Fig. 1.2 shows. In the sleep period, a node powers off its wireless interface in order to save energy. At the beginning of each active period, the node wakes up and gets ready to transmit. An important concern related to sleep scheduling is whether the delay or throughput behavior is deteriorated. Therefore, the crucial issue in the design of sleep scheduling protocols is to strike a trade-off between the overall performance and power saving. Extensive efforts can be classified into coordinated scheduling and random scheduling (also called asynchronous scheduling). Generally, coordinated sleep scheduling approaches can potentially achieve better performance with the centralized coordination of sleep schedules than random scheduling.

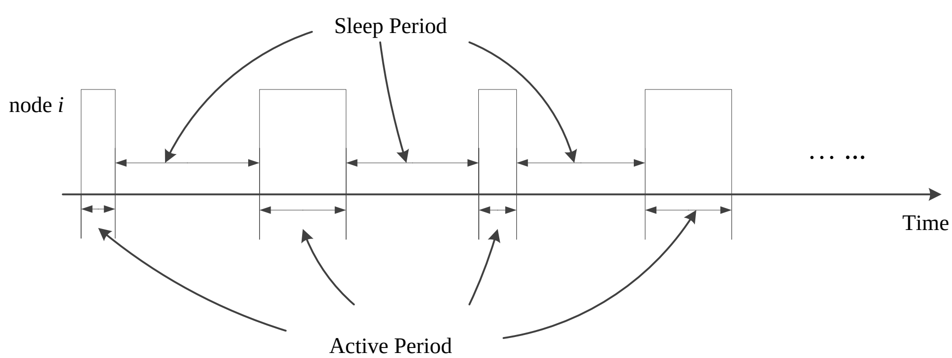

Figure 1.2: An illustration of operation of sleep scheduling.

1.2.3 Energy-efficient Routing in the Network Layer

Energy-efficient routing is proposed to reduce end-to-end transmission energy cost of data communications in wireless ad hoc networks. Different routes consist of different nodes in the topology and hence determine a unique transmission path related to energy resources. Typically power-aware routing protocols select a path connecting a pair of source and destination node that minimizes the total transmissions power over all the nodes in the selected path. Most existing power-aware routing protocols assume that wireless links are reliable. However, in wireless networks, various factors like ambient noise, fading and interference can lead to packet losses due to transmission errors. A retransmission mechanism is commonly employed in the link layer to recover from packet losses. Therefore, the total transmission power associated with a pre-selected path in the power-aware routing protocols fails to capture the actual energy spent in packet delivery considering potential retransmissions. Energy-efficient reliable routing protocols that take account of the quality of wireless links are hence proposed to find best paths requiring less number of retransmissions. It is worth to mention that those best path routing (BPR) protocols all follow a conventional design principle of traditional wired networks: the best routes are pre-determined before data transmissions and all data flows from the source and destination follow the selected routes until the path is updated.

Opportunistic routing (also called anypath routing), an integrated routing and MAC technique has recently overturned this principle. Instead, opportunistic routing protocols allow multiple forwarders to opportunistically deliver packets to the destination, accounting for their time-variant channel conditions. The general idea of OR is that, for each destination, a set of next-hop candidate forwarders are selected and prioritized. When a data packet is to be forwarded, the highest priority node among candidates that received it will be chosen as the next-hop. It leverages the wireless broadcast advantage (WBA) to mitigate the impact of packet losses: the packet transmission for a node can be heard by its neighboring nodes, so that the probability of successful reception by at least one node within these forwarders can be much higher than that of just one fixed next-hop. It is envisioned that OR avoids retransmissions as long as the packet makes forward progress towards the destination and thereby reducing the total energy consumed. OR protocols are confirmed to outperform BPR protocols in terms of the total energy consumption with lossy broadcast links. One fundamental issue in designing an energy-efficient OR protocol is how to select and prioritize the forwarder list to minimize the total energy cost.

1.3 Motivations and Objectives

As indicated, the overall energy consumption at a wireless node involves many aspects including transmission, reception, idle listening, overhearing and transmission collisions. By and large, existing energy-efficient routing protocols have focused on controlling the transmission power of the wireless interface at senders. Although significant in terms of reducing the power consumption in the wireless transmitter of a sender, it does little to conserve the power among the other nodes: receivers, forwarders, and even nodes not involved in this communication. Therefore, energy-efficient routing supporting coordinated sleep scheduling has the potential benefit of higher network-wide energy efficiency in the wireless ad hoc networks. Nevertheless, the function of coordinated sleep scheduling exerts an influence on the actual performance achieved by energy-efficient routing protocols. As we discussed before, OR protocols exploit the gains of multi-receiver diversity in order to enhance energy efficiency. On one hand, increasing the number of potential forwarders by an OR protocol reduces the transmit energy consumed at a transmitter. On the other hand, it on the contrary reduces the opportunities of powering off the wireless interface at those potential forwarders compared with BPR protocols. There is a trade-off between the reduction of the transmission energy and the potential increase of the total energy required for receiving at those forwarders. Therefore, energy savings achieved by the proposed energy-efficient routing protocols should be revisited with the introduction of coordinated sleep scheduling. Moreover, existing OR protocols needs to be analyzed in terms of energy efficiency in comparison with BPR protocols.

The objective of this thesis is mainly to study the energy-efficient routing supporting coordinated sleep scheduling protocols. To the best of our knowledge, we are the first to identify the impact of coordinated sleep scheduling on energy-efficient routing performances. In this thesis, we first propose the framework of energy-efficient routing to support coordinated sleep scheduling which can accommodate both BPR and OR protocols for a fair evaluation. Then, we report on comprehensive performance evaluations to investigate this impact under different network conditions. Through detailed comparisons of the performance metrics in terms of the total energy consumption, throughput, packet delay and energy efficiency by extensive simulations, we study the effects of network parameters (such as the traffic load and node density) on the actual system performance achieved by BPR and OR protocols respectively. By doing this, the simulation results shed some light on improving network-wide energy efficiency with the energy-efficient routing protocols in wireless ad hoc networks.

1.4 Outline of the Thesis

The reminder of this thesis is organized as follows. In Chapter 2, we present a brief literature survey on current sleep scheduling and energy-efficient routing protocols. The comprehensive system models under consideration and the research problem are given in Chapter 3. Chapter 4 presents the framework of the proposed energy-efficient routing supporting coordinated sleep scheduling. Chapter 5 describes the performance evaluation for demonstrating the impact of coordinated sleep scheduling on different routing protocols. Moreover, the impacts of traffic load and node density regarding different network condition are studied via computer simulations. Finally, Chapter 6 gives concluding remarks of this research and outlines the possible future work.

Chapter 2

Background and Literature Survey

In this chapter, we discuss the essential background knowledge about sleep scheduling and energy-efficient routing protocols and explain some related work research. The existing sleep scheduling and energy-efficient routing protocols that are proposed for wireless ad hoc networks are reviewed in such a way that each protocol is briefly explained, and cons and pros are identified.

2.1 Sleep Scheduling in Wireless Ad Hoc networks

2.1.1 Random Sleep Scheduling

Random sleep scheduling specifies each node to decide its own sleep schedule, thereby releasing the requirement of clock synchronization [7]. In random scheduling, sender and receiver are usually not scheduled to be active concurrently. Therefore, a wake-up mechanism is prerequisite to facilitate the communications with each other. In wake-up mechanisms, either neighbor nodes sleep schedules need to be exchanged in advance or active nodes are found by exchanging some certain control messages. In the latter case, normally periodic beacons, request-to-send (RTS) frames or long preambles assist the transmitter to discover active neighbors. Fig. 2.1 shows the procedure of a wake-up mechanism done by handshakes proposed in [8], where S refers to the sender and R denotes the receiver. Node S transmits beacons periodically and R replies to the beacons with acknowledgement (ACK) whenever it is active, so S is able to discover and transmit data to R. Random sleep scheduling can make the network protocol robust and adaptive to topology change, which is more attractive in a low-loaded WSN. But it introduces latency for waiting for a receiver to wake up and cannot guarantee the worst-case delay. Related studies mainly focus on minimizing the waiting time [9] and improving the power efficiency [10] [11].

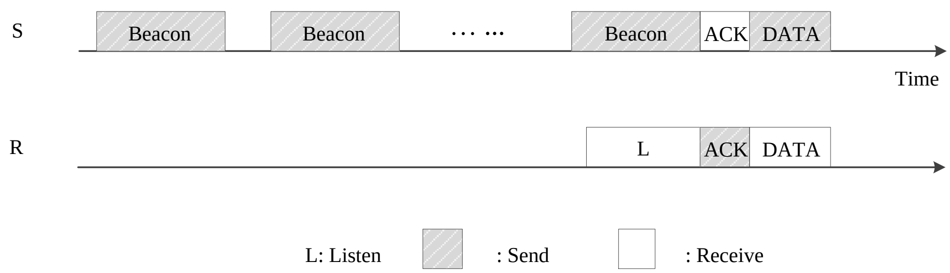

Figure 2.1: Illustration of the wake-up mechanism for communication under random sleep scheduling.

2.1.2 Coordinated Sleep Scheduling

In coordinated scheduling mechanisms, a common wake-up period can be coordinated by broadcasting sleep schedules with neighbors so that the waiting time can be greatly decreased. For instance, institute of electrical and electronics engineers (IEEE) 802.11 has defined power saving mode (PSM) [12], In the PSM, time is mainly divided into periodic beacon intervals. At the beginning of a beacon interval, all nodes are required to stay awake for a period called ad-hoc ad hoc traffic indication message (ATIM) window. A transmitter sends an ATIM frame to inform its destination for the arrival traffic. Then, the pair of sender and receiver keeps awake during the rest time of the beacon interval for packet transmission. Other nodes without the traffic demand are allowed to power off the wireless interface for energy saving. Let us illustrate the IEEE 802.11 PSM by means of an example as shown in Fig. 2.2. Consider nodes A, B and C, and node A has packets for node B during this beacon interval. Thus, node A sends an ATIM request, node B receives it and replies with an ATIM ACK in ATIM window. After the ATIM window ends, node A transmits a data packet to B. Since node C has not sent or received any ATIM request during the ATIM window, it goes to the sleep mode during this period. By adopting the similar idea, S-MAC [5] and R-MAC [13] are proposed for multi-hop transmissions with the purpose of reducing the end-to-end delay. Green-wave [14] further investigates the fundamental limits of latency and throughput achieved by coordinated sleep scheduling in wireless ad hoc networks in the presence of multiple flows. Obviously, coordinated scheduling is more appropriate for supporting the multimedia traffic with delay and throughput requirements. Moreover, it is more applicable to work with any routing protocols and can be solely determined by the routing protocols. In this thesis, we adopt the function of coordinated sleep scheduling as the principle of powering off operations.

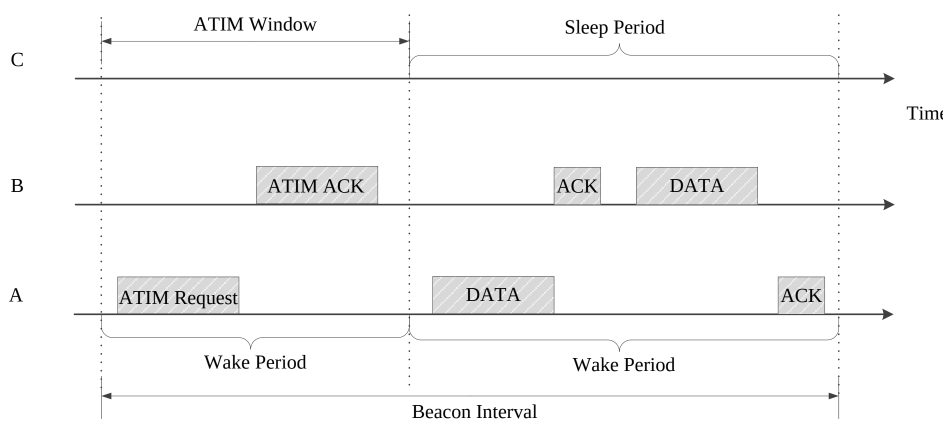

Figure 2.2: Illustration of the IEEE 802.11 power saving mode.

2.2 Energy-efficient Routing in Wireless Ad Hoc Networks

During the last decades, extensive research on energy-efficient routing protocols have been carried out towards the wireless ad hoc networks. The main target is route selection for terminating nodes to pick the most appropriate path for maximizing the route metric of energy efficiency. Normally, the metrics with respect to energy efficiency are consequences of states of energy resources and factors affecting those resources. The usual way of an energy-efficient route selection is to define the energy cost based on those metrics, and then to employ the maximization/minimization policies to the cost of all available paths, called route cost, so that we could find a most energy-efficient path to connect the source node and destination node. In the following, we provide a comprehensive overview of up-to-date contributions in this research area, which are roughly divided into three categories: power-aware routing, energy-efficient reliable routing, and opportunistic routing. In each category, we select some representative routing protocols for review and mainly discuss their route metrics. It is notable that we focus on their features and limitations, but the specific implementation details related to the routing protocols, such as the particular information acquisition and dissemination are not stressed.

2.2.1 Power-aware Routing Protocols

Transmission and Receiving Power: The first routing algorithm concerning on the energy consumption is proposed in [15], called minimum total transmission power (MTTP) to minimize total transmission power in order to substitute the early used minimum hop routing (MHR). It intends to select the route with the minimum total transmission power, and a simple Dijkstra algorithm can be used to find this route. A result from such approach is the possibility to select routes with more hops than other routing algorithms, and hence more nodes involved in routing packets consume more energy and cause a larger delay. Following [15], a multi-access protocol with signaling (PAMAS) protocol is presented in [6]. The study defines the energy cost considering the transceiver power that consists of power used when receiving data as well as transmission power. Note that the route selected by PAMAS involves a fewer hops than that by MTTP algorithm. There is a trade-off of route selection between a path consisting of more hops with short range and fewer hops with long range.

Geography-based Power: The authors in [16] developed minimum energy communication network (MECN) with the aid of geographic information aiming at consuming the least amount of energy possible. Relay Region and Enclosure Region identified in this paper are described in Fig. 2.3, redrawn from [16]. Relay Region of node i refers the region that all nodes in this region will save more energy if data are transmitted through them than direct transmission. Therefore we could draw the Enclosure Region consisting of such nodes that the node i can reach, and they are called neighbors with which node i only maintains the communications. By using a much localized search, the nodes in the relay region are eliminated and the node only picks up the immediate neighborhood to be candidates. The routing protocol is divided into two phases: The first phase is to construct the sparse graph by using the local search. The second phase is to find the minimum power consumption route on the enclosure graph by using the distributed Bellman-Ford algorithm. Obviously this approach causes additional complexity and overhead of searching the sparse graph, and global position system (GPS) and power control mechanism are needed to implement the protocol, which may be impractical in some cases.

Energy Dissipated in Route Discovery and Transmission: A well-known routing protocol called power-aware routing (PARO) is proposed in [17]. It is a dynamic power control routing scheme that helps to minimize the transmission power needed to forward packets between nodes in the wireless ad hoc networks. It is based on the fact that additional forwarding nodes between pairs of source and destination significantly reduces the transmission power. The main idea is that one or more intermediate nodes are elected as redirectors to forward packets so that the length of individual hops is shorten, which reduces the aggregate transmission power. The energy cost accounts for the energy consumption of route discovering to find the minimum path, and transmission energy for delivering data and ACK packets.

Energy Dissipated in Signalling and Transmission: For timely path setup and ef-

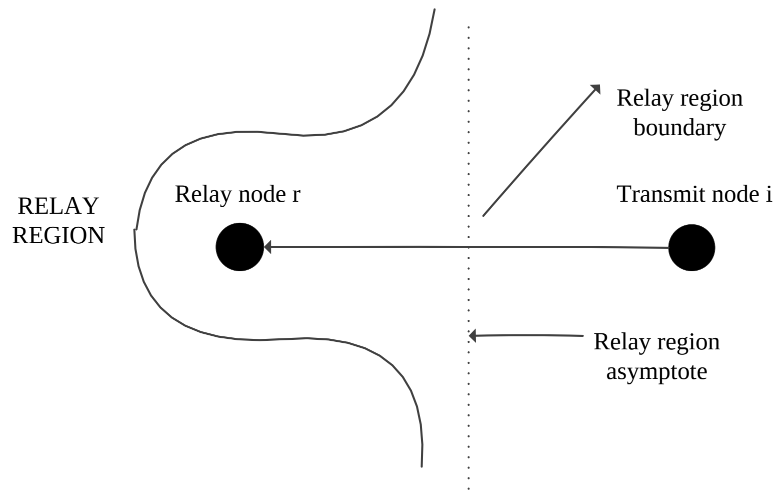

Figure 2.3: Relay region of transmit-relay node pair.

ficient path maintenance, progressive energy-efficient routing (PEER) protocol is proposed in [18]. It inserts the energy cost into the internet protocol (IP) header, and every node monitors the data packets exchanged in its neighborhood to intercept the corresponding link costs. In route discovery, it allows the intermediate nodes to rebroadcast such a packet only if it is from the shortest path or comes from a path with the same number of hops but the energy consumption is lower. In route maintenance, the observing node records and monitors the data packets exchanged in its neighborhood and collaborates with its neighbors to look for a more energy-efficient path when the topology changes. Fig. 2.3 illustrates how the three operations work related to topology changes around a node D, redrawn from [18]. For instance, in the remove operation, if node E becomes the neighbor of node D, and the link cost from D to E is smaller than 3+2, then node D will update the route table by setting node E as the next hop for the destination.

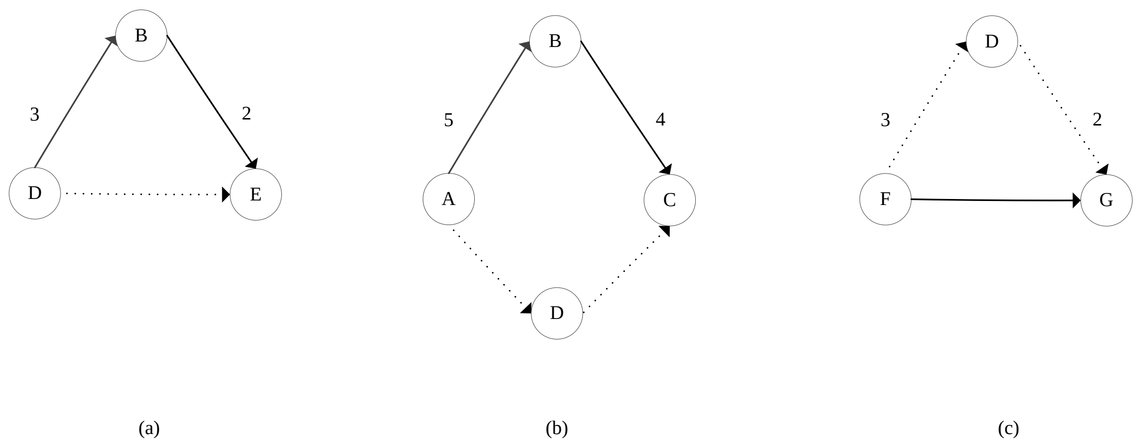

Figure 2.4: Remove (a), Replace (b) and Insert (c).

2.2.2 Energy-efficient Reliable Routing Protocols

Reliable Transmission Power: The following wireless routing protocols, such as minimum total reliable transmission power (MTRTP) protocol in [19] and reliable minimum energy routing (RMER) in [20] both indicate that proper metric should include the total energy spent in reliably delivering the packet to its final destination. The choice between a path with many short-range hops and another with fewer long-range hops is non-trivial, but involves a tradeoff between the reduction in the transmission energy for a single packet and the potential increase in the frequency of retransmissions. The RMER further addresses the practical limitation of the maximum allowable number of retransmissions into the formulation of the energy cost. The main contribution of them is they first propose the reliable transmission energy consumption models in end-to-end retransmission (EER) and hop-by-hop retransmission (HHR) system respectively. The drawback here is that each node should be aware of the packet error probability on its outgoing links, and the additional latency caused by retransmissions is not considered.

Energy Dissipated in Signalling and Reliable Transmission: A more intensive study in [21] considers the signaling power consumption, and proposes more comprehensive energy consumption models in the MAC layer. It holds that without considering such energy consumption, these protocols may tend to use a larger number of intermediate nodes, thus resulting in more energy consumption. The comprehensive energy consumption models for carrier sense multiple access (CSMA), multiple access with collision avoidance (MACA) and IEEE 802.11 in EER and HHR are formulated respectively. Further, a comprehensive minimum energy routing (CMER) is proposed by based on those models.

2.2.3 Opportunistic Routing Protocols

In this subsection, we first review the OR framework and explain how transmission energy is saved as against the BPR protocols for reliable transmissions. Then, we present the existing OR protocols according to the routing metrics. The complete survey of existing OR protocols in the context of wireless ad hoc networks and several design challenges can be found in [22] [23] [24]. The majority of previous studies focuses on the definition of route metric together with selection of forwarder list, acknowledgement coordination (AC) [25] [26] [27] [28] and models and analyzes the performance in OR [29] [30]. One fundamental challenge is how to optimize the forwarder list and assign the priority to each potential forwarder so as to maximize the network performances.

Review of OR Framework: The opportunistic packet forwarding process within a time slot consists of three periods: data transmission, AC and forwarding. Consider a sender node u and three neighboring nodes v_1, v_2, v_3, Fig. 2.5 shows the timing diagram for OR operation within a single time slot. In general, the network layer passes down a set of candidate forwarders and the MAC layer takes a final decision on the node to use depending on transmission outcomes and their priorities. Next we introduce the detailed operations through this example.

- Data Transmission: Before data transmission, the sender u selects a subset of neighboring nodes as its forwarder list $\{v_1, v_2\}$ and assigns a priority to each candidate within the forwarder list. A single fixed length packet is then transmitted from sender u, which piggybacks this prioritized forwarder list for this packet in its header.

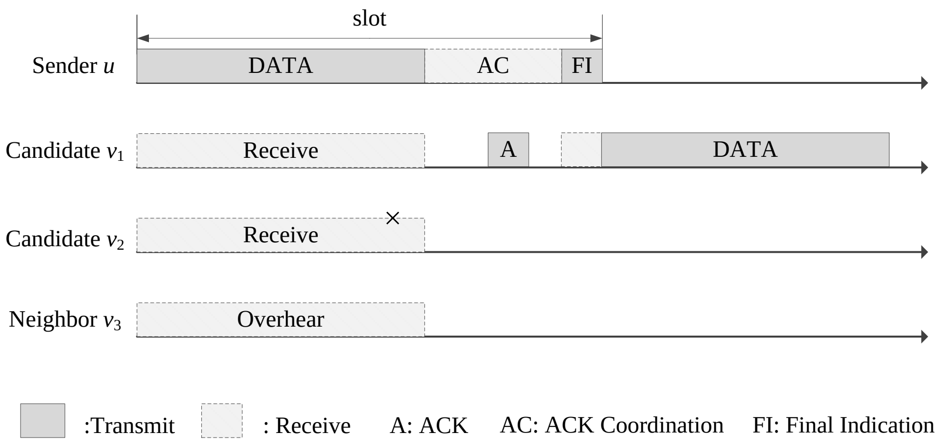

Figure 2.5: A timing diagram illustrating the OR operation within a single timeslot.

- Acknowledge Coordination: Each candidate that successfully receives the packet, such as v_1, responds with an ACK. Other nodes such as node v_3 discard the packet immediately after the reception because it is not included in the forwarder list. AC process is initiated in the MAC layer among candidates to avoid the feedback implosion and to guarantee that only the candidate with the highest priority forwards the packet. For instance, those ACKs are staggered in time according to their priorities in a TDMA-like approach by imposing a strict scheduler on the access to the medium [31]. Candidates refrain from forwarding the packet as long as they overhear a higher priority ACK. Therefore, they reach an agreement on which candidate is responsible of forwarding the packet. But duplicate packets forwarding is still possible when some receiving nodes in the forwarder list cannot hear from each other directly. Multiple nodes may hear a packet and unnecessarily forward the same packet. Fig. 2.6 illustrates such a problem. In Fig. 2.6, assume v_1, v_2 and v_3, v_4 are the only neighboring pairs among the candidates. If no communications are used to resolve duplicates, a lower priority node v_3 may be unaware of an ACK sent by the higher priority nodes like v_1 still forwards the packet, thereby causing the harmful effect on the overall network performance.

- Forwarding: A handshake mechanism can be employed after the AC period to address duplicate forwarding in TDMA systems [28]. The sender u accumulates all the ACK responses and then transmits a final indication (FI) message that provides instructions for the future packet forwarding. As a result, the problem of duplicate forwarding is effectively resolved.

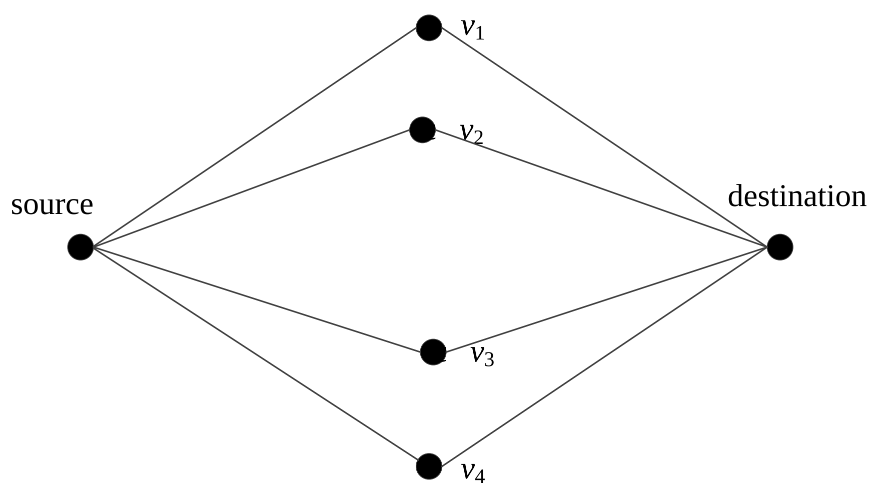

Figure 2.6: An example for illustrating the duplicate packet forwarding.

By leveraging the gains of multi-receiver diversity, the probability of successful transmission to at least one candidate in the forwarder list can be much higher than that to a fixed next-hop node in the BPR protocols. Therefore, OR is confirmed to reduce the end-to-end transmission energy on condition that packet makes progress towards the destination.

Geographic Distance: It is acknowledged that geographic random forwarding (GeRAF) protocol is considered as one of the earliest articles related to OR protocol [32]. It first applies the OR principle into duty-cycling WSN where node availability is random due to the random sleep scheduling. It uses geographic positions and selects the candidate forwarders that are closer to the destination than the current node, as shown in the Fig. 2.7. All active candidates assess their forwarding priority based on how close they are to the destination. Thus three candidate nodes R1, R2 and R3 are prioritized in the forwarder list in such an increasing order. It leverages the WBA and hence greatly reduces the sleep-wake delay in the duty-cycling network. However, this simple approach trivially guarantees loop freedom, but making progress in the physical distance does not necessarily guarantee the improvement of end-to-end network performance such as the end-to-end transmission energy consumption.

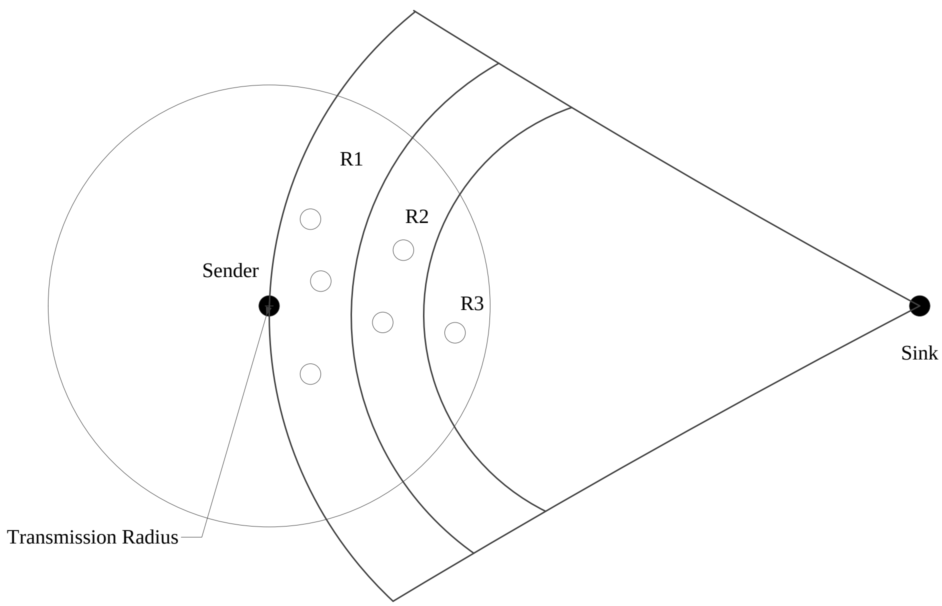

Figure 2.7: Illustration of forwarding regions and its partitions in GeRAF with three priority regions $R1 < R2 < R3$.

Expected Number of Transmissions: Inspired by GeRAF, extremely opportunistic routing (ExOR) is proposed in [33] that is especially designed for WMN that fully takes advantage of wireless broadcast. The main idea of it is that the prioritized forwarder list is first preselected, and only nodes in the forwarder list forward the packet in the order of forwarding priority that is estimated based on the expected transmission numbers (ETX), i.e., the number of transmissions required to move a packet along the shortest path. Then each sender chooses each hop of a packets route after the transmission for that hop, so that the choice can reflect the transmission outcomes. The deferred choice gives each transmission multiple opportunities to make progress and hence greatly increases the packet delivery ratio and throughput. As a single-path route metric, ETX serving as the base of forwarder list selection cannot reveal the impact of OR on the average number of transmissions.

Expected Anypath Transmissions: Zhong proposes the concept of expected anypath transmissions (EAX) in [34] which captures not only the expected number of transmissions for successfully transmitting a packet from the source to at least one candidate forwarder, but also the expected number of transmissions for forwarding the packet in turn to the destination. Thus EAX indicates the extent of gain possible with OR over BPR. Based on the definition of EAX, [30] proposes a discrete Markov chain approach to model the forwarder list selection mathematically and uses this model to compare the performances that are achieved by different forwarder list selection algorithms. Considering that EAX-based protocols do not provide any proof of optimality, least cost anypath routing (LCAR) is proposed to compute the optimal candidate forwarders [35]. Two basic tradeoffs are first taken into account in the design of the optimal OR protocol. On one hand, increasing the number of candidate relays decreases the forwarding cost. On the other hand, it increases the probability that the actual route deviates from the shortest path route and ultimately even introduces loops in the routing topology. The second trade-off is related with the duplicate transmissions since more candidate nodes also increase the risk of duplicate forwarding. The main contribution is that so called the anypath Bellman equation in the form of EAX instead of the conventional single-path route metric used in ETX-based protocols. Similar to the Bellman-Ford algorithm in BPR protocols, LCAR exhaustively searches all possible forwarder lists to find the paths with minimum costs.

Queue Backlogs: Das in [31] developed an OR extension of IEEE 802.11 MAC layer, where the dramatic modification is that RTS in distributed coordination function (DCF) is replaced with multicast RTS (MTS) that consists of all the next hop receiver addressed. More than one clear-to-send (CTS) can be responded and it designs a TDMA-like approach to coordinate the CTS transmissions. The next hop receivers are assigned a priority order, which can be determined by their distance or the queue backlogs. These CTS transmissions are deferred in order of their priorities. When the transmitter receives a CTS packet, it transmits the DATA frame to the sender of CTS with the highest priority. Moreover, an ETX-based routing protocol according to the distance or the queue backlogs is put forward corresponding to the proposed MAC. Therefore, it can achieve a higher throughput and effectively decrease the congestion in the network based on the proposed MAC protocol.

Expected Energy Costs: Above OR protocols mainly aim at maximizing the spectral efficiency for large file transferring in wireless static mesh networks where energy saving is not a primary concern. To demonstrate the energy efficiency benefit of OR, several OR protocols targeted to maximize the energy efficiency are proposed. [35] specifically considers the application of LCAR to a low-rate, duty-cycled wireless network to reduce the transmission energy consumption of packet forwarding. Simulation results show that the average energy cost of LCAR is approximately 40% lower than ETX-based OR protocols. The energy-efficient opportunistic routing (EEOR) protocol adopts the similar optimal framework and mainly focuses on the minimization of total transmission energy in OR [36]. It first carefully calculates the expected energy cost and then chooses the forwarder list such that the total transmission energy is minimized. Extensive experimental results show that EEOR performs better than ExOR and BPR in terms of the energy consumption, packet loss ratio and average delay. [37] also employs the energy consumption as the routing metric. The main contribution lies in that it provides the theoretical bounds in the performance analysis of BPR and OR in terms of energy consumption, throughput and delay distribution.

2.2.4 Comparison of the Existing Routing Protocols

After describing the various energy-efficient routing protocols, Table 2.1 lists the fully comparisons between those energy-efficient routing protocols.

2.3 Summary

In this chapter, a literature review for sleep scheduling and energy-efficient routing protocols in wireless ad hoc networks is presented. First, random sleep scheduling and coordinated sleep scheduling protocols are analyzed, respectively. After that, an overview of the current energy-efficient routing protocols for wireless ad hoc networks is briefly introduced to provide a broad view of the existing solutions from power-saving routing protocols, energy-efficient routing protocols and opportunistic routing protocols. Finally, a qualitative comparison of the existing energy-efficient routing protocols is provided.

Table 2.1: Comparison between the current energy-efficient routing protocols.

Protocol	**Metric**	**Pros**	**Cons**
MTTP	Transmission Power	1.Simplicity.2 Reduces transmission power compared with MHR.	1.More hops are apt to be selected causing more energy.2.Larger delay.
PAMAS	Transceiver Power	1.Involves few hops reducing total energy consumption.	1.Large signaling overhead.
MECN	Transceiver Power	1.Determines a minimum power topology.2.Achieves better energy savings by dividing the Relay Regions.	1.Additional complexity and overhead.2.GPS and power control are needed.
PARO	Transmission power and route discovery power consumption	1.Elects re-directors for energy saving.2.Considers the energy consumption during the phase of route discovery.	1.Power Control is needed. 2.Larger signaling overhead.
PEER	Transmission power and signaling power	1.A more comprehensive energy model is adopted.2.A fast response to topology change.	1.Complexity.2.Heavy burden for monitoring at relay node
MTRTP	Reliable transmission power	1.Captures the energy consumed by retransmissions. 2.EER and HHR are both considered.	1.Packet error probability is needed in advance.
RMER	Truncated reliable transmission power	1.Applicable to a more practical scenario.	1.Complexity of implementation.
CMER	Reliable transmission and signalling power	1.Models the energy consumption in CSMA MAC protocols.	1.Not feasible for other MAC protocols.
GeRAF	Geographic distance	1.Reduces the sleep-wake delay under random sleep scheduling.	1.Doesnt guarantee the end-to-end performance.2.Only Applies for duty-cycled WSN
ExOR	ETX	1.Improves the packet delivery ratio and throughput.	1.Cannot capture an accurate expected number of transmissions for delivering a packet.
Zhong's	EAX	1.Captures the expected number of transmission for opportunistically forwarding a packet.	1.Doesnt provide any proof of optimality.
Das's	ETX,queue backlogs	1.Improves the throughput.2. Eases the network congestion.	1. Only suitable for DCF operation.
LCAR	EAX,sleep time ratio	1.Gives the proof of optimality of EAX.2.Reduces the energy consumption in duty-cycling WSN.	1.Complexity.2.Only feasible to duty-cycling WSNs.
EEOR	Expected energy cost	1.Further reduces the energy consumption compared with ExOR.	1.Doesnt consider the energy caused by AC process.

Chapter 3

System Model and Problem Statement

In this chapter, we present the system models under consideration from a top-down approach. We further make several fundamental assumptions in our evaluation. Then we identify our research problem regarding the proposed system model.

3.1 Network Topology and Configuration

Consider a grid network on a square plane with N equal-sized cells with one node located at the center of the cell. All wireless nodes are assumed to be static and share a common wireless channel. The multi-hop wireless network is modeled by a communication graph $G = (V, E)$, where V is a set of wireless nodes (vertices) and E is a set of directed links (edges), respectively. Each node is assigned a distinct integer identifier between 1 and $N = |V|$. Each directed link is labeled according to the node pairs (u, v) for $u, v \subseteq V$ in which u and v are transmitter and receiver nodes, respectively. Each source node is assumed to initiate a single traffic flow. The source-destination pairs (S, D) are given, where S and D denote the set of source and destination nodes, respectively.

Wireless links are usually prone to transmission errors, which results in packet drops before reaching the destination. However, the dropped packets still consume a high amount of energy during their passage through the network. We assume that wireless links are independent and denote the packet error probability (PER) as $p_{u,v}(x)$ for link (u, v), which is the probability that a transmission of data packet of size x bit over the link (u, v) is not successful.

We assume that nodes are powered by battery and support adjustable transmission power due to the practical considerations. But each node has no function of dynamic power control, i.e., each node cannot control its transmission power at the packet level. Such an approach is used to represent all the commercially available devices that are pre-programmed with a discrete set of power settings. The transmit power $P_t(u)$ at node u belongs to a finite set of transmit powers, denoted as $S(u) = \{P_t^1(u), P_t^2(u), ..., P_t^m(u)\}$, where m means the number of allowable transmit power levels at each node. We define $N(u)$ as the neighboring nodes set of node u. Note that the number of neighboring nodes of a node may vary with the change of used transmit power. Specifically, for BPR protocols, the transmit power $P_t(u)$ can be represented by the minimum transmission power from the discrete set of $S(u)$ over the wireless link (u, v) that satisfies the targeted packet error rate Th. However, for OR protocols, the transmit power $P_t(u)$ is denoted as the minimum power required for transmission from node u to the farthest forwarder node at node u from $S(u)$. In this thesis, we assume that by adjusting the transmit power, the data transmission rate does not change with the transmit power.

3.2 Link Layer

Consider a time-slotted system with slots normalized to integral units $t \in \{0, 1, 2, ...\}$. All the nodes are synchronized with the aid of GPS device. Our focus of study is on the assessment of the benefit of energy efficiency of routing protocols. Therefore, we adopt a sender-based TDMA MAC protocol to minimize the influence of collisions on the actual energy cost from the link layer. In addition, we introduce the link-layer retransmission mechanism to combat with the unreliability of wireless channel, where a lost packet due to the transmission errors can be recovered from the successive retransmissions. The remarkable difference from all the existing works is that we integrate the functions of coordinated sleep scheduling into the proposed MAC protocol. In the following, we discuss the details of those main functions in the link layer. Since our objective is to study the energy cost alone, we do not consider other factors such as link congestion, buffer overflow etc. In other words, each link has an infinite buffer.

3.2.1 Restricted TDMA MAC

The primary issue in designing a restricted TDMA MAC protocol is how to formulate the set of simultaneous links. A variety of wireless interference models of varying levels of complexity have been proposed and used in the literature. Generally, there are two common interference models in the existing literatures, known as protocol interference model and physical interference model, respectively [38] [39]. Let us suppose node u_i transmits over the channel to the receiver node v_i in the grid network. Then this transmission can be permitted if the following conditions are satisfied for every other node u_j simultaneously transmitting over the channel:

The Protocol Interference Model

$$|u_j - v_i| \geq (1 + \sigma)|u_i - v_i| \tag{3.1}$$

where the quantity σ models the guard zone specified by the protocol to prevent a neighboring node from transmitting at the same time. Another interference model is known as the physical interference model, which is based on additive interference and signal to interference plus noise ratio (SINR) threshold over a realistic channel. This model is motivated by the decoding strategies employed in the wireless physical layer technologies.

The Physical Interference Model

$$\frac{P_T \cdot A|u_i - v_i|^{-\alpha}}{N_0 + \sum_{j \neq i} P_T|u_j - v_i|^{-\alpha}} \geq \beta \tag{3.2}$$

where N_0 denotes the ambient noise power level, α and A denotes the parameters of adopted channel model regarding the signal attenuation, and P_T denotes the maximum transmit power at each transmit node. The threshold of SINR β in a fading environment is usually specified in such a way that the targeted link error rate Th is satisfied for reliable transmission. In fact, those two interference models have been verified as equivalence under the same channel model and transmission scheme [40].

Lemma 1: We can directly conclude from the literatures [14] [38] [39] that if each transmission is limited to communicate within a communication range of d with the maximum transmit power P_T, then simultaneous transmissions can take place among links that are at least $R(d)$ away, without violating aforementioned interference models. The value of $R(d)$ is determined by the parameters in the interference model, such as $\sigma, N_0, P_T, A, \alpha, \beta$, etc.

After obtaining a reasonable value of $R(d)$ based on the interference models, we can design an appropriate TDMA schedule for each node. We group a block of K cells within a square with size $R(d) \times R(d)$ into a macro-cell as shown in Fig. 3.1. Each node is allocated with a unique slot from the sequence of K successive slot, i.e., the length of one TDMA frame is equal to K slots. By doing this, we are able to use the round-robin scheduling on all macro cells in each time slot, such that transmitting cells (in dark) that are always $R(d)$ away can transmit data simultaneously without violating the requirement of maximum packet error rate in the system.

3.2.2 Truncated Hop-by-Hop Retransmission

For practical consideration, we adopt the truncated HHR mechanism to ensure link level reliability system. In truncated HHR retransmission mechanism, a lost data packet is retransmitted by the sender node at each hop. An ACK is responded by the receiver to the sender when it receives the packet correctly. An absence of ACK after a data packet transmission implies that the packet is corrupted, and then the sender continues to retransmit the packet until it receives an ACK or the maximum allowed number of transmission attempts Q_m is reached. The packet will be dropped by the sender if it

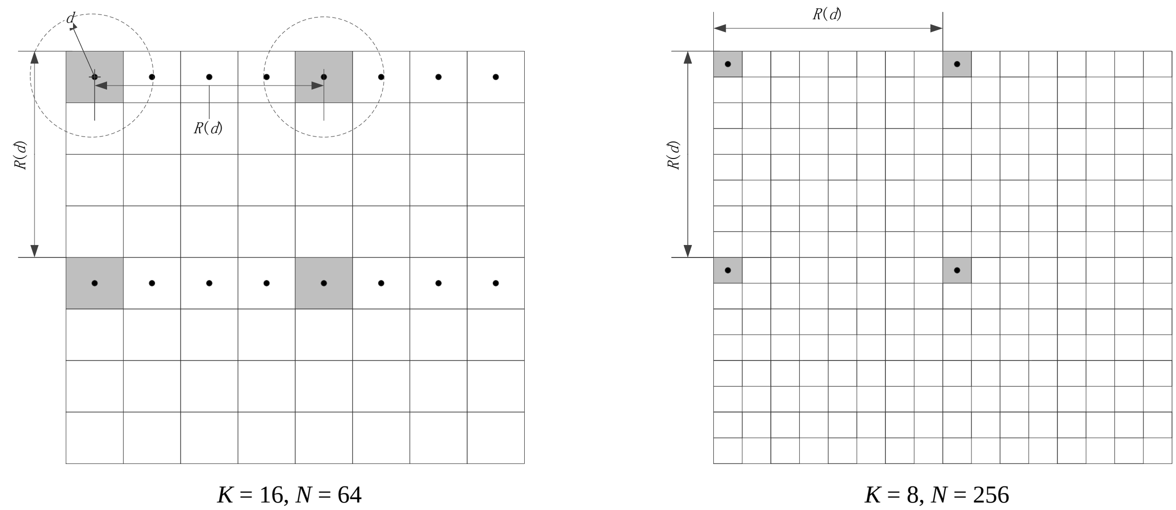

Figure 3.1: An illustration of restricted TDMA MAC under different node density scenarios with $K = 16$ and $K = 64$, respectively. The dots at the center of each cell are the nodes, and grey cells can transmit simultaneously.

cannot be successfully delivered within the pre-configured maximum number of attempts. Obviously, if each link is reliable, the end-to-end packet delivery will also be reliable.

3.3 Physical Layer

3.3.1 Transmission Scheme

Consider an single-input single-output (SISO) system, where each transmitter use a common transmission scheme consisting of a specific modulation and forward error correction (FEC) code pair according to the physical layer specification of IEEE 802.11g [41]. The channel rate associated with the transmission scheme is denoted as R. At the receiver, coherent demodulation and maximum likelihood (ML) decoding criteria are used. The decoded bit streams are mapped to packets, which are delivered to the data link layer.

3.3.2 Radio Propagation Model

To capture the effect of a propagation environment on a radio signal, we consider the free-space path loss model for the large-scale propagation model, augmented by a small-scale model modeling Rayleigh fading as presented in [37] [42] [43]. The Rayleigh channel is characterized by a slow, flat fading, i.e., the channel remains invariant over transmissions of a frame, but is allowed to vary from frame to frame. The channel quality is captured by a single parameter, namely the received signal to noise ratio (SNR). Under the Rayleigh channel adhering to the channel model, the instantaneous γ per frame is thus a random variable with the probability density function (PDF) as [44], given by

$$p_\gamma(\gamma) = \frac{1}{\gamma} e^{\frac{\gamma}{\bar{\gamma}}} \tag{3.3}$$

where $\bar{\gamma} = E(\gamma)$ is the average received SNR at the receiver, which is related to the large-scale path loss model. While we consider here a special case with Rayleigh fading, it can be easily extended to other fading channel models by adopting the general Nakagami-m model instead [45].

The transmitted signal is affected by the free-space path loss as in [46]. Consider a link between a pair of transmitter and receiver (u, v) with distance $d_{u,v}$. We denote P_T and P_R as the transmit power and received signal power respectively. According to the Friis formula [45], the average received SNR $\bar{\gamma}$ is given by

$$\bar{\gamma} = \frac{P_R}{N_0} = \frac{G_t G_r c^2 P_T}{(4\pi)^2 f_1 f_c^2 d_{u,v}^{\alpha} N_0} \tag{3.4}$$

where G_t and G_r are constants depending on the transmitter and receiver antenna gains, respectively, f_c is the carrier frequency, c is the speed of light, f_1 is a loss factor and α is the path-loss component. So the channel parameters in the physical interference model $A = \frac{G_t G_r c^2}{(4\pi)^2 f_1 f_c^2}$.

3.4 Research Problem

One fundamental research problem related to energy efficient wireless ad hoc networking is how to achieve the maximum energy efficiency over wireless ad hoc networks. Currently, energy-efficient routing and coordinated sleep scheduling are powerful candidate tools to resolve this problem. Therefore, energy-efficient routing supporting coordinated sleep scheduling has the potential benefit of improving network-side energy efficiency. From the literature review in the Chapter 2, we observe that the prior studies of energy-efficient routing and coordinated sleep scheduling are usually conducted separately with the assumption that each component is independent with the other. However, actual energy saving achieved by sleep scheduling is coupled with different routing protocols. For instance, OR protocols require more neighboring nodes to stay awake for receiving the packet, which on the contrary reduces the opportunity of entering the sleep mode compared with other energy-efficient routing protocols with the BPR principle. The reduction of transmit energy at the transmitter node is achieved with the expense of increased energy consumed at those forwarder nodes. Therefore, the performance of energy-efficient routing protocols needs to be revisited with the incorporation of coordinated sleep scheduling. As far as we know, there is a lack of systematic studies on the energy-efficient routing supporting coordinated sleep scheduling. We are first to identify this problem and conduct the performance evaluations of different energy-efficient routing protocols with the incorporation of coordinated sleep scheduling. However, the real-world link layer and physical layer protocols contain many finer engineering details, such as MAC, control packet overhead, modulation, coding, interference and fading which cannot be easily captured into an analytical model. Therefore, we resort to simulations to get a better understanding of impact of coordinated sleep scheduling on energy-efficient routing performances. Here we identify two progressive research problems, which are

Problem 1: To propose a framework of energy-efficient routing protocols supporting coordinated sleep scheduling, which can facilitate the operations of exiting routing protocols with principles of BPR and OR, respectively;

Problem 2: According to the proposed framework, we intend to investigate the effects of the network parameters such as the traffic load and node density on the overall system performances achieved by different energy-efficient routing protocols to illustrate the impact of coordinated sleep scheduling. The basic performance metrics in terms of the total energy consumption, aggregate end-to-end throughput, packet delay and energy efficiency are used for comprehensive comparison in simulations.

3.5 Summary

In this chapter, we describe the system models covering considerable aspects of a wireless ad hoc network including the network topology, MAC, retransmission mechanism, transmission scheme and radio propagation. The system models can be used to depict a realistic static wireless ad hoc networks. Then, two research problems are identified based on the adopted system model.

Chapter 4

Energy-efficient Routing Supporting Coordinated Sleep Scheduling

In this chapter, we present our proposed framework of energy-efficient routing which supports coordinated sleep scheduling. At first, the function of coordinated sleep scheduling is integrated into the adopted MAC protocol. Then, we describe three typical energy-efficient routing protocols used in our performance evaluation, which are MHR, RMER and EEOR. The main focus is to provide an analysis of energy cost in each routing protocol, which serves as the fundamental part of the corresponding routing algorithms. Note that one primary premise before discussing routing protocols is that the energy costs in different routing protocols should work in the system model under consideration.

4.1 Coordinated Sleep Scheduling

We assume that the wireless nodes are capable of powering off the radio interface during a certain period within a time slot. This allows a node to enter the low-power sleeping mode when it does not have a packet to send or to receive. In this study, we adopt the function of coordinated sleep scheduling to facilitate the routing operations with respect to BPR and OR protocols, respectively.

In the adopted sleep scheduling protocol, a time slot is divided into two periods, namely **WAKE** and **DATA** periods, respectively. Generally, all the nodes wake up at the beginning of the WAKE period in one time slot. During the WAKE period, transmitters with the communication demand send a signaling packet of traffic indicator to inform its intended receiver nodes. Meanwhile all other nodes keep listening to the channel for the possible traffic indicator from any of the neighbors. During the DATA period, all the nodes are allowed to power off the radio interface when it does not have a packet to send or to receive in this time slot. Such coordinated sleep scheduling protocol has been widely discussed in research on periodic sleep scheduling. Fig. 4.1 illustrates the sleep scheduling combined with different routing operations with the BPR and OR principles, respectively. In the following, we discuss the framework of routing operations combined with the function of coordinated sleep scheduling using the example shown in Fig. 4.1. Suppose in this time slot, the sender node u has a data to transmit and v_1, v_2, v_3 are three neighbor nodes within its transmission range. For the BPR protocols, we assume that node v_1 is the receiver which has been specified in advance, while v_1 and v_2 are two candidate forwarders within the forwarder list Fwd of OR protocol.

WAKE Period: When a data packet is ready for transmission, sender u transmits an RTS signalling packet with packet length L_{RTS}^{BPR} or L_{RTS}^{OR} regarding the different routing protocols, and all the nodes within its broadcast range v_1, v_2, v_3 are required to receive the packet. It contains the forwarder list and their priorities. Note that for BPR protocols, only one forwarder is specified in the field of RTS.

DATA Period: During the DATA period, a data packet with packet length L_d is transmitted. The routing operation varies with respect to different routing protocols. In the following, we present the detailed operation of BPR and OR, respectively.

- BPR Packet Transmission: Sender u unicasts the data packet to the specified receiver node, v_1, while nodes v_2 and v_3 turn off their radio during the rest of time slot to preserve energy. Only node v_1 is required to receive the data packet. After an ACK responded from receiver v_1 is received at node u, the data transmission is complete. Otherwise, sender u will retransmit this data packet in the next available time slot.

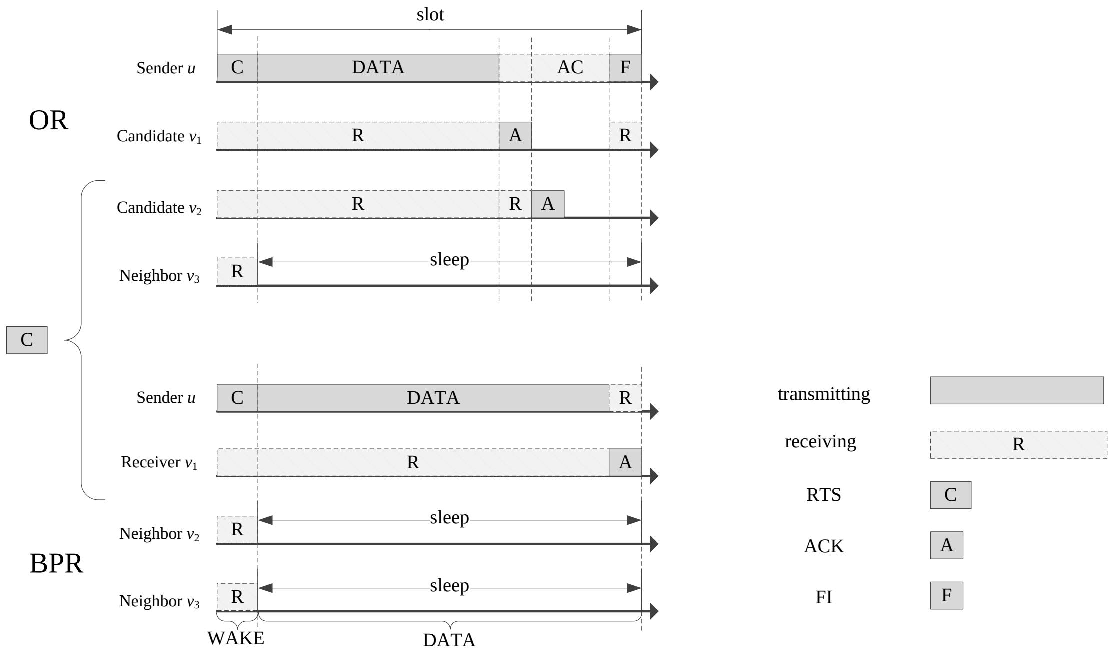

Figure 4.1: A timing diagram illustrating the routing operation within a single time slot.

- OR Packet Transmission: Sender u multicasts the data packet to the multiple candidate nodes specified in the forwarder list $\{v_1, v_2\}$. Node v_3 then turns off the wireless interface to enter the sleep mode as it is not involved in the data transmission in this time slot. Here we introduce a TDMA-like approach in AC period for the OR protocols based on [28]. When an intended candidate receives the data packet, it responds by an ACK packet. These ACK transmissions are deferred in time in an order of their priorities. The first candidate with the highest priority transmits the ACK as soon as it successfully receives the data packet, the second one after a period equal to the time to transmit an ACK, and so on. Finally, sender u transmits an FI message that indicates the node v_1 to take the responsibility of forwarding the packet. The packet length of FI message is denoted as L_{FI}. The duration of AC period is predefined according to the maximum candidates C_m that can be used for practical considerations.

We assume that signaling packets, such as RTS, ACK and FI, with a small packet length are not subject to transmission errors, while data packet transmissions in general encounter link failures as in [28]. It is worth to mention that those assumptions are made mainly for simplicity of the calculations of the expected energy cost in the following. Since the packets are relatively short, it is reasonable to assume that the channel remains relatively constant for the entire time slot. Thus once the data packet goes through, we assume that ACK and FI transactions are successful. Note that our model does not assume any special energy models. Parameters related to the power used in this study will be described in the Chapter 5 for the calculations of the energy cost in simulations.

4.2 Energy-efficient Routing Protocols

4.2.1 Minimum Hop Routing

The MHR protocol uses the route metric of hop count where the link quality for this metric is a binary concept: either the link exists or it does not [47]. The criterion for having a link from node u to v is as follows: There is a link from u to v, if the PER over the link satisfies the targeted link error rate. The primary advantage of this metric is its simplicity. Once we know the network topology, it is easy to compute and minimize the hop count between a source and a destination. Moreover, computing the hop count requires no additional measurements and communication overhead, unlike the other metrics described in this section.

4.2.2 Reliable Minimum Energy Routing

Expected Transmission Count: Due to the limit of the maximum number of retransmissions in our system, a data packet might be retransmitted a random number of times not greater than Q_m. Therefore, we cannot directly apply the result from the works in [19] [36] where the number of transmissions is described as a geometrically distributed random variable. Let $E[rp, L_d, Q_m]$ be the expected number of times that sender u needs to transmit a packet of length L_d to deliver it to v under the routing protocol rp, where $rp = 0$ denotes the RMER protocol and $rp = 1$ denotes the EEOR protocol. For the RMER protocol, the relation between $E[0, L_d, Q_m]$ and PER is obtained according to Appendix A in work [20], given by

$$E[0, L_d, Q_m] = \frac{1 - p_{u,v}(L_d)^{Q_m}}{1 - p_{u,v}(L_d))}. \tag{4.1}$$

Energy Cost of RMER: Here we define $C_u^d(0, N(u), v)$ as the expected total energy cost of sending one data packet from node u to node v regarding the flow with the destination node d when the routing protocol rp is used. The energy cost of a link in RMER protocol is the total amount of energy consumed in the transmitting and the receiving nodes to exchange a data packet. Denote the expected total energy cost at the receiver v is C_v^d, and the total power consumption at transmitter and receiver as P_{tr} and P_{rc}, respectively.. According to the results from [20], $C_u^d(0, N(u), v)$ can be written in the form of Bellman-Ford expression, given by

$$C_u^d(0, N(u), v) = E[0, L_d, Q_m]\frac{L_d}{R}(P_{tr} + P_{rc}) + \frac{L_{ACK}}{R}(P_{tr} + P_{rc}) + C_v^d. \tag{4.2}$$

Finding the Optimal Next-hop Node: We adopt the well-known Bellman-Ford algorithm for RMER protocol to determine the optimal next-hop node. Refer to Appendices for details of algorithm A.1.

4.2.3 Energy-efficient Opportunistic Routing

Expected Transmission Count: Let ρ denote the probability that a data packet sent by node u is received by at least one node in the forwarder list Fwd. Then, we can obtain that $\rho = 1 - \prod_{v_i}^{|Fwd|} p_{u,v_i}(L_d)$. The the expected transmission count $E[1, L_d, Q_m]$ can be derived as follows:

$$E[1, L_d, Q_m] = \frac{1 - \rho^{Q_m}}{1 - \rho}. \tag{4.3}$$

Energy Cost of EEOR: The idea of formulating the energy cost of EEOR protocol is totally different from that of traditional BPR protocols. In EEOR protocol, we first compute the expected cost and the forwarder list Fwd at node u based on the expected cost of its neighbors whose expected cost of sending a data to the given target node has already been computed. The main task here is how to choose a subset of neighboring nodes $N(u)$ for the forwarder list such that the average energy cost for node u to send a data packet to the target d is minimized. We define the expected energy cost at the transmitter node u as $C_u^d(1, N(u), Fwd)$ for the flow with destination node d, where all nodes in the forwarder list have been already sorted in an increasing order by expected energy cost, i.e., $Fwd = v_1, v_2, ..., v_{|Fwd(u)|}$, where $i < j \Rightarrow C_{v_i}^d < C_{v_j}^d$. The communication cost for agreement in the AC period is omitted in [36], and the expected energy mainly consists of two parts. The first part denotes the energy consumed by hopping the data packet to at least one candidate node. The second part denotes the energy consumption during the forwarding process starting from the candidate node to the destination node. Let $C_u^s(d, Fwd)$ denote the first part energy, i.e. expected energy cost that node u must consume to send a packet to at least one node in the forwarder list Fwd. According to the results from [36], it can be calculated as follows:

$$C_u^s(d, Fwd) = E[1, L_d, Q_m] P_{tr} \frac{L_d}{R}. \tag{4.4}$$

When at least one node in the forwarder list receives the packet successfully, we need to calculate the expected cost to forward the packet sent by node u, which is denoted by $C_u^f(d, Fwd)$. By introducing the AC period, only one node from the forwarder list that received the packet will forward the packet. Then, the forwarding energy cost can be calculated as follows: Given the prioritized forwarder list is $Fwd = v_1, v_2, ..., v_{|Fwd(u)|}$, the probability that node v_1 forwards the packet is $1 - p_{u,v_i}$ and the expected cost of v_1 is $C^d_{v_1}$. Then, node v_2 will forward the packet with probability $p_{u,v_i}(1 - p_{u,v_2})$ and the cost is $C^d_{v_2}$. Basically, node v_i forwards the packet if it receives the packet and node v_j, $0 < j < i$ did not receive the packet, and in this case, the cost is $C^d_{v_j}$. Hence, the expected cost can be computed as follows:

$$B = (1 - p_{u,v_1})C^d_{v_1} + \sum_{i=2}^{|Fwd|}(\prod_{j=1}^{i-1} p_{u,v_j}(1 - p_{u,v_i})C^d_{v_i}). \tag{4.5}$$

Because the expected cost B is obtained under the condition that at least one forwarder in the forwarder list receives the packet, we can compute $C^f_u(d, Fwd)$ by

$$C^f_u(d, Fwd) = B \times E[1, L_d, Q_m]. \tag{4.6}$$

Overall, the expected cost of data transmission is given by

$$C^d_u(1, N(u), Fwd) = C^s_u(d, Fwd) + C^f_u(d, Fwd). \tag{4.7}$$

Finding the Optimal Forwarder List: The basic idea is that the computation of expected cost is recursive and executed at each node independently, then the expected cost is radially calculated staring from the destination outward to the rest of the network. Through the exhaustively searching that is similar to the Bellman-Ford algorithm, the optimal forwarder list is thus determined, and its optimality has been proved in [35]. The distributed algorithm only requires local coordination for forwarding decisions once the expected total energy cost has been computed. Refer to Appendices for details of algorithm A.2.

4.3 Summary

In this chapter, we present our framework of energy-efficient routing to support coordinated sleep scheduling for the performance evaluation. First, a detailed description of how to integrate the function of coordinated sleep scheduling into our adopted MAC protocol is given. Then, three representative energy-efficient routing protocols used in our simulation are discussed, where both energy cost and routing algorithms for each routing protocol are described.

Chapter 5

Performance Evaluations

To evaluate the impact of coordinated sleep scheduling, we implemented those three routing protocols on destination sequenced distance vector routing (DSDV) in our Matlab simulator, which are MHR, RMER, and EEOR with/without the capability of coordinated sleep scheduling, respectively (hereafter referred to as **w SS/wo SS**). In the following, we first introduce the performances metrics measured in the simulations. Then, we discuss several important issues in the simulation methods, and present the simulation results for various scenarios.

5.1 Performance Metrics and Impact Factors

To measure the performance of each scheme, we choose five performance metrics for evaluating the performances in our simulations:

- **Packet Delivery Probability (%)**, which is the ratio of successful received packets over the total number of packets sent at each hop or along a route. We calculate the packet delivery probability (PDP) over all active links participating in the data forwarding.

- **Total Energy Consumption (J)**, which is the total average energy consumption throughout one simulation run. We not only consider the transmit energy for each data packet, but also the energy consumed by the control packets and the energy dissipated in the link layer during the simulation run.

- **Aggregate end-to-end Throughput (Mbits/second)**, which is the number of all useful data bits that are successfully delivered to the destination nodes in a second. We exclude the control packets overhead in the calculation of throughput.

- **Packet Delivery Delay (second)**, which is the average packet delay being the duration from the time instant that a packet is ready for transmission at the source node to the instant that the packet is successfully received at the destination node.

- **Energy Consumption per Packet (mJ)**, which is the normalized energy consumption required by one data packet that is successfully delivered through the network. This metric is used to evaluate the network-wide energy efficiency of the different power-saving protocols.

Let us now characterize the tunable system parameters, and we intend to investigate the impact of two parameters on the overall performances, which are

- **Traffic load**, defined as the overall average payload data arrival rate at all the source nodes. Here the traffic load is denoted as the proportion T_l of the channel rate R. The traffic load is equally distributed among all the source nodes on average. A higher traffic load increases the strength of interference which will affect the actual packet delivery probability. We will first examine the changes in performance gains as the traffic load varies over the network;

- **Node density**, defined as the total number of nodes N located in the same area. A higher node density provides more links for data forwarding for both RMER and OR protocols, while it may consume more energy for opportunistic receptions in the EEOR protocol.

5.2 Simulation Methodology

Consider an SISO system, the antennas at nodes are omnidirectional ($G_t = G_r = 1$), $f_1 = 1$ (no system losses not associated with propagation) and the carrier frequency is in the unlicensed 2.4GHz band. Unless specified, we set α for free space propagation, but our approach can be extended to other propagation scenarios by modifying the path-loss component. The maximum number of transmissions $Q_m = 3$ in HHR system, and the maximum number of candidates for OR protocols is set to be $C_m = 6$. The targeted packet error rate Th within the transmission range of a node is set to be 0.2 such that the maximum packet loss ratio, i.e., the probability that a packet cannot be successfully delivered to the receiving node within the number of allowed transmissions, is below 1%, which is the typical operation of IEEE 802.11b/g in an outdoor environment. The traffic model uses the Poisson arrival traffic with randomly chosen source-destination pairs for each simulation. For each source and destination pair nodes u and v, u will generate the data packets per flow according to a Poisson process. Each simulation run lasts for 200 seconds and each result is obtained from the average of 50 runs. Observe that the network may be congested with an increase of traffic load, so we consider a simple algorithm to balance the network load efficiently. For example, the ongoing traffic flow from each node should not exceed the capacity bound. Each node prefers to choose the next hop node with a low traffic load when different forwarders can achieve similar performance.

5.2.1 Capturing Packet Transmission and Reception

According to the physical layer specification of popular IEEE 802.11g, multiple transmission modes are available, with each mode consisting of a specific modulation and FEC code pair as shown in Table 5.2 [12]. Three modulation schemes are available, which are binary phase shift keying (BPSK), quadrature phase shift keying (QPSK) and quadrature amplitude modulation (QAM). Each node uses the common transmission mode 3 consisting of QPSK modulation and convolutional code (CC) with coding rate 3/4. The data rate associated with the specific modulation and code pair R is 18Mbps.

Table 5.1: IEEE 802.11g physical layer specification.

Transmission Mode	**Data Rate (Mbps)**	**Modulation**	**Coding Rate**
0	6	BPSK	1/2
1	9	BPSK	1/2
2	12	QPSK	1/2
3	**18**	**QPSK**	**3/4**
4	24	16-QAM	1/2
5	36	16-QAM	3/4
6	48	64-QAM	2/3
7	54	64-QAM	3/4

Apart from the packet transmission, packet receptions over an error-prone radio medium, i.e., whether one packet are successfully decoded or not, must be decided at the receiver node. There have been great efforts to capture packet errors of data transmissions over a wireless link. Most of them adopt a deterministic packet reception model where the packet is successfully received when the strength of received SNR or SINR is above a threshold [20] [48]. However, in practical packet-level radio communication systems, packet errors for coded transmissions are no longer independent with each other [37]. Therefore, a reasonable packet reception model for coded transmissions should take into account of various aspects, such as the modulation scheme, coding scheme, radio propagation, ambient noise, interference, demodulation and decoding scheme, etc. However, it is well-know that precise characterization of wireless links is a challenging problem. The exact closed-form expressions for PERs at the packet level for the coded modulations are by far not available. As a result, most recent studies adopt a measurement-based packet-level model that correlates the instantaneous PER with SNR or SINR [37] [43] [49].

To simplify the simulation of the physical layer, we adopt the SNR-based technology to capture the packet receptions over wireless links in our simulations as in [37] [43]. Each successful packet reception at the receiver node follows the probability of successful packet reception. The probability of successful packet reception (1-PER) is obtained based on the value of received SNR, i.e., a pre-configured SNR-to-PER mapping profile that is locally available to the node. In this study, we treat the interference as ambient noise, and hence the aforementioned SNR-to-PER mapping can be used to further represent the SINR-to-

PER mapping. Then, we are motivated to search for an accurate SINR-to-PER mapping for modeling the packet reception regarding our transmission scheme. We follow the approach of [37] [43] for fitting a polynomial to the instantaneous PER versus received SNR (SINR) γ, where the coherent demodulation and ML decoding are used at the receiver, and the corresponding model of PER is derived with the aid of bit-by-bit Monte Carlo simulations. To facilitate the modeling of packet receptions, we rely on the following approximate PER expression as in [43]:

$$PER(\gamma) = \begin{cases} 1, & 0 < \gamma < \gamma_p \\ a \cdot e^{-b \cdot \gamma}, & \gamma \geq \gamma_p \end{cases} \tag{5.1}$$

where the fitting parameters a, b and γ_p are transmission mode-dependent, and are obtained by least-squares fitting the approximate PER model to the exact PER derived from practical simulations. Fig. 5.1 shows the SNR (SINR)-PER curves with different transmission modes in the IEEE 802.11 g standard. In the case of our transmission mode 3, we can obtain 67.6181, 1.6883 and 3.9722 (dB) for parameters of a, b and γ_p respectively directly from the results presented in the literature [43].

5.2.2 Obtaining SINR Threshold β

To ensure the requirement of the maximum packet loss ratio, we need to determine an appropriate TDMA schedule and the transmit power for each node before initiating the packet transmissions in our simulations. Recall from the link layer model described in Chapter 3, the TDMA schedule depends on the SINR threshold β specified in the physical interference model for a given Th. The key question is how to express the SINR threshold β in the form of the average PER (the ratio of the number of incorrectly received packets over those transmitted packets). We modify the approach as suggested in the literature [43] to model the relation between β and average PER. According to [43], we can evaluate the average PER for the proposed Rayleigh fading channel based on the instantaneous PER model. Taking expectations over channel realizations, the average PER for a given value

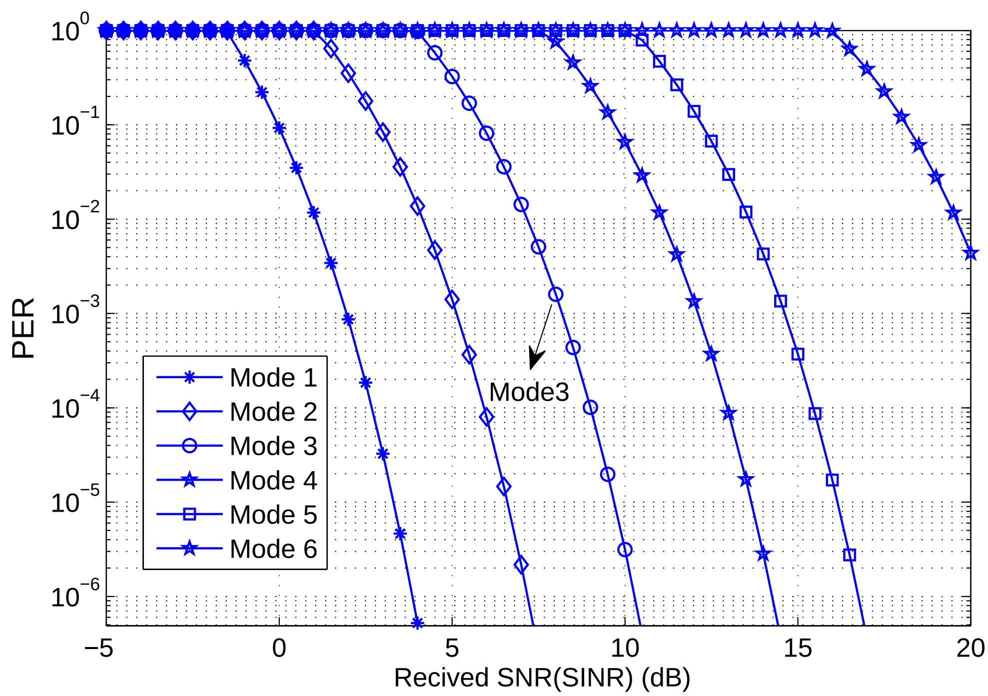

Figure 5.1: Packet error rate denoted by the fitting curves to the exact PER of the transmission modes from mode 1 to mode 6 in IEEE 802.11 g.

of average SINR at the physical layer is as follows:

$$\overline{PER} = \int_0^{\infty} PER(\gamma) \cdot p_\gamma(\gamma) d\gamma = \int_0^{\gamma_p} p_\gamma(\gamma) d\gamma + \int_{\gamma_p}^{\infty} a \cdot e^{-b\gamma} p_\gamma(\gamma) d\gamma. \tag{5.2}$$

Therefore, the threshold of SINR β used in the physical interference model can be thus represented as Th according to the results of the Equations (3.2) and (5.2). Then, we can divide the macro cells and design the TDMA schedule for each node. Note the average SINR expressed in the physical interference model is the worst-case SINR, which does not account for the randomness of interfering individuals. Therefore, the requirement of maximum packet loss rate can be fully ensured by adopting the worst-case SINR. Similarly, each transmit node can determine the minimum transmit power required by nodes to satisfy the requirement of targeted link error rate.

5.2.3 Estimation of Average Packet Error Rate

After capturing the packet transmission and reception, another important issue for our reliable routing protocols is to estimate the average PER over each wireless link. For the implementation of reliable routing in terms of RMER and EEOR protocols, the average PER of a link must be known to compute the energy cost of that link. According to the SINR-based approach used in the packet reception, if the statistical characteristics of interference are available, the accurate estimation of the average PER can be obtained. However, adding the interference-awareness is not a simple task. Numerous research works are carried out towards the statistic interference modeling [48] [50]. It is pointed out that the statistical characteristics of interference depend on the statistics of the individual interfering signals. The randomness of the individual interfering signals can be due to several aspects, such as link layer operation, propagation effects, interferer location and traffic pattern, etc. Therefore, this consideration raises a question: How well the average PER can be estimated and predicted to enhance the overall network performances?

Due to the fact that none of existing model-based methods takes a full consideration of our system model, we resort to the measurement-based approaches proposed in [51] [52] [53] [54] to estimate the average PER over each link. In those approaches, each node measures the packet errors using observed interference locally. The worst-case interference part in the formulation of SINR is replaced by the measured value. Then, the estimated average PER over each incoming link is sent back to the corresponding transmit node. By doing this, the transmit node is aware of the average PER of each outgoing link. In addition, average PER estimation can be updated in order to capture the changes of interferers. In our simulations, we set the worst-case average PER obtained from the subsection 5.2.2 as the initial average PER over each link. The average-PER update period is always 2 second in simulations. Clearly, the average-PER update period plays a role in trade-off between performance enhancements and messaging overhead resulting from frequent average PER updates. In the simulation results, we will demonstrate the impact of the average-PER update period on the actual overall performances of routing protocols.

5.2.4 Modeling Power Consumption

There is another important issue in our simulation, which refers to the calculation of the total power consumption. To facilitate the calculation of power consumption for the different transmit power, we consider the commonly adopted power consumption model as in [55]. The power consumption related to a packet transmission is abstracted into two distinct parts: The first part is the fixed circuit power to run the transmitter or receiver circuitry. The second part represents the power consumed by the transmit power amplifier to generate the required output power for data transmission over the air. For receivers, the energy consumed by a receiver only involves the first part including the low noise amplifier (LNA) of receiver. We define A_u as the power required to run the transmitter circuit at sender node u, and B_v for that at the receiver node v. Let κ_u be the power efficiency of transmitter amplifier, where $0 < \kappa \leqslant 1$, then we can calculate the total power consumption at the transmitter and receiver side as follows:

$$P_{tr} = A_u + \frac{P_t(u)}{\kappa_u} \tag{5.3}$$

$$P_{rc} = B_v. \tag{5.4}$$

Based on the datasheet of Cisco Aironet Wireless CardBus Adapter [56] and above Equations (5.3) and (5.4), we can derive $A_u = 1.19$ W and $B_v = 1.08$ W. For each node, we consider ten levels of transmit power starting from $P_t^1(u) = 10$ mW and increasing in steps of 10 mW up to the maximum transmission power $P_t^m(u) = 100$ mW. For example, the values of power consumption associated with the maximum transmit power in transmit, receive, idle and sleep mode are 1.78 W, 1.08 W, 0.67 W and 0.02 W, respectively.

5.2.5 Simulation Process

Overall, the values of fixed parameters used in the simulations are listed in Table 5.2. Fig. 5.2 illustrates the overall simulation process. We abstract the main function of each network layer as a module denoted as one box in the figure. As we can see, each module is not working independently. Those three modules are interconnected and coordinated to facilitate the useful information exchange so as to complete the data forwarding. In the following, we summary the main functions of different modules to illustrate the working process of our simulation.

- **The Physical Layer**: The physical layer module is mainly responsible for the S-INR-to-PER mapping and the average PER update. At the input of the physical layer module, the instantaneous SINRs are determined according to the results of routing decision and transmission opportunity obtained from the network layer and link layer, respectively. The transmission outcomes regarding each data packet transmission and the average PERs are determined after the processing of the physical layer module. Those results are then passed to the above link layer and the network layer, respectively.

- **The Link Layer**: The link layer module in our simulations mainly plays the roles of performing the TDMA schedule, sleep scheduling, retransmission and actual forwarding. More specifically, the TDMA schedule is obtained in advance and determines the transmission opportunity of each node. The function of sleep scheduling is executed based on the results of routing decisions obtained from the network layer. The function of retransmission is triggered by the transmission outcomes in terms of success or failure, which are passed from the physical layer. Meanwhile, the node state information (active or sleep state) for each node are delivered to the network layer for the calculation of routing metrics. By using the results of routing decisions and transmission outcomes, the forwarding decision is hence made.

- **The Network Layer**: The main task of the network layer module is to calculate the routing metric according to all the information acquired from both the link layer and the physical layer, such as the average PERs and node states. Then, the routing decisions regarding each node is derived and passed to the lower layer modules. The link layer uses the results of routing decisions to perform the sleep scheduling, while the physical layer uses the routing decisions to determine which nodes are needed to calculate the SINR.

Table 5.2: Values of fixed parameters related to energy consumption used in simulations.

Parameter	**Value**
Network area	$400 \times 400m^2$
Topology	Grid
Fading model	Rayleigh
Path loss model	Free-space loss
Transmission rate (R)	18 Mbps
Transmitter antenna gain (G_t)	1
Receiver antenna gain(G_r)	1
Carrier frequency (f_c)	2.4 GHz
System loss factor (f_1)	1
Path-loss exponent (α)	-70 dBm
Thermal noise power (N_0)	2.4 GHz
Power consumption of transmitter circuit (A_u)	1.19 W
Power Consumption of Receiver Circuit (B_v)	1.08 W
Power efficiency of transmission amplifier (κ_u)	17 %
Minimum transmit power ($P_t^1(u)$)	10 mW
Maximum transmit power ($P_t^m(u)$)	100 mW
The number of allowable transmit power (m)	10
Steps of increasing transmit power	10 mW
Power consumption of listening (P_1)	0.67 mW
Power consumption of sleeping (P_s)	0.02 mW
Retransmission scheme	HHR
Maximum number of transmissions (Q_m)	3
Maximum number of candidates (C_m)	6
Targeted packet error rate (Th)	0.2
Data packet size (L_d)	1080 byte
physical layer (PHY) header	128 bit
MAC ACK packet size (L_{ACK})	112 bit + PHY header
RTS packet size in BPR protocol (L_{RTS}^{BPR})	160 bit + PHY header
RTS packet size in OR protocol (L_{RTS}^{OR})	240 bit + PHY header
FI packet size in OR protocol (L_{FI}^{OR})	112 bit + PHY header

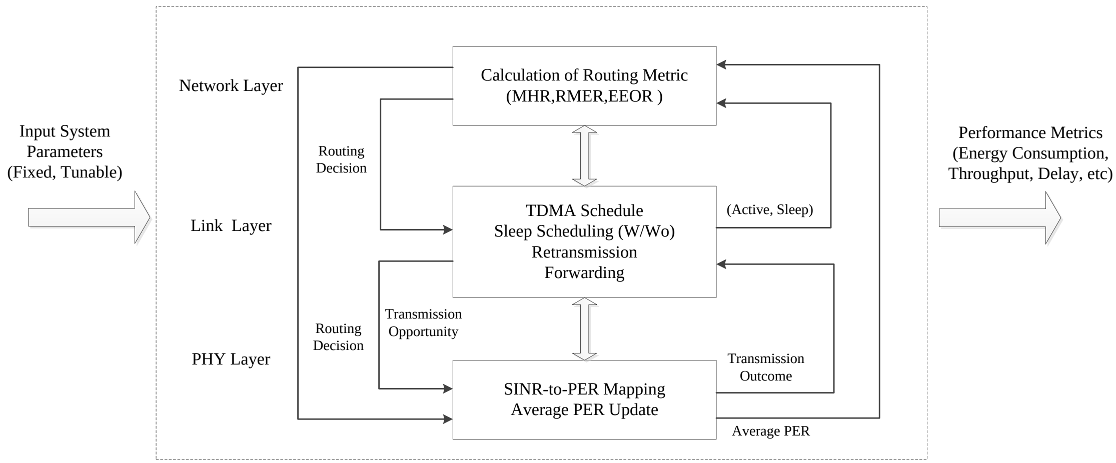

Figure 5.2: The diagram to illustrate the overall simulation process.

5.3 Simulation Results

5.3.1 Impact of Average-PER Update Period

We examine the effect of the average-PER update period on the routing performance. In practice, the degree of interference caused by each interfering node on a link is not the same. It varies depending on the position and the amount of generated traffic of the interferer with respect to the routing decision as well as the path loss characteristics. The basic idea of rerouting is to redistribute traffic within the network, capturing the effects of variation in interference degree at each link. Therefore, paths found by routing algorithms can avoid the areas with high interferences, reducing the number of packet errors and retransmissions. Hence it results in lower energy consumption and higher network throughput. One goal here is to maximize network performance in terms of the throughput. In this set of experiment, we look into the length of average PER update period needed to achieve this goal.

Example 1: The maximum transmit power P_T is 100 mW and the total number of nodes N is 64. We group a size of 16 nodes in a macro cell and totally we have four macro cells in the coverage. The topology in this example is shown in Fig. 5.3. We randomly select 16 nodes as the source nodes and the traffic load Tl is 40%. The RMER wo SS algorithm is used as the power-saving protocol with different PER update periods.

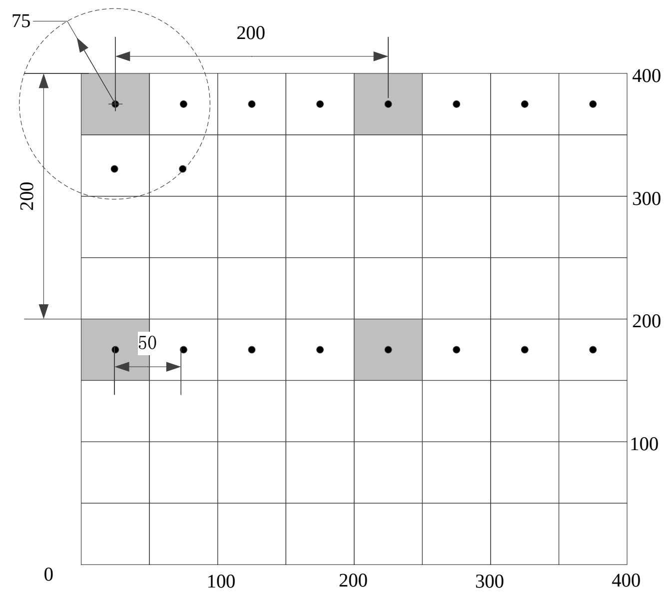

Figure 5.3: The topology for the example 1 and 2 with 64 nodes and 4 macro cells.

Then, we did simulations to demonstrate the throughput performances and the total energy consumption when different average-PER update periods are adopted as shown in Figs. 5.4 and 5.5. On one hand, a smaller period of average-PER update induces over-frequent link cost updates and results in a large messaging overhead for the update of the route metric in term of the average PER. On the other hand, an inappropriately long update period cannot respond to the changes in the interference degree of a node after route decisions are made, which otherwise deteriorates the achievable performance. From Figs. 5.4 and 5.5, we can observe that the average-PER update interval for the optimal performance is at the time scale of seconds. In the following experiments, we always set the update period at 2 seconds.

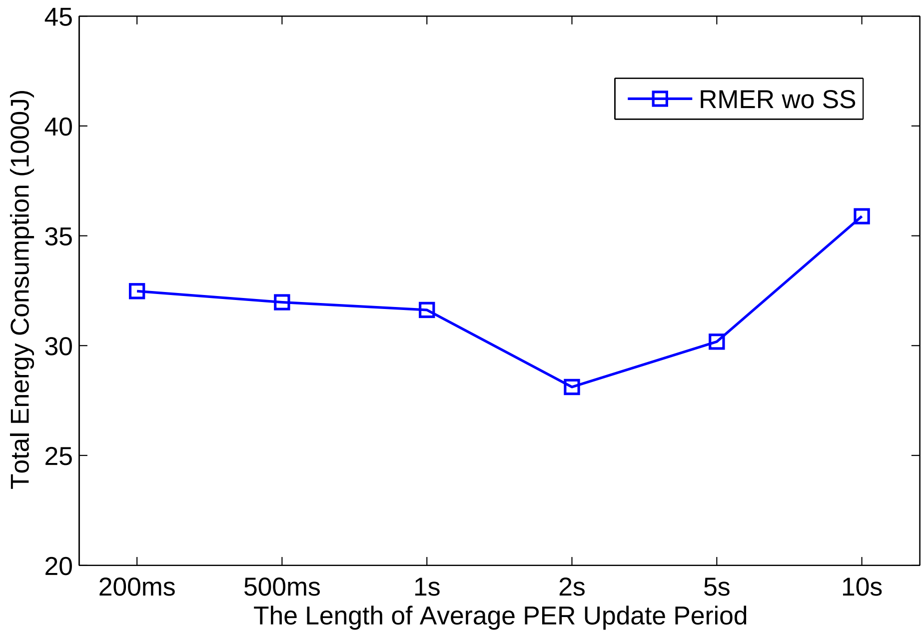

Figure 5.4: Comparison of the total energy consumption versus the length of average PER update period.

5.3.2 Impact of Traffic Load

Example 2: The maximum transmit power P_T is 100 mW and the total number of nodes N is 64. The network topology is the same as in example 1. We randomly pick 16 nodes as source nodes where each source node initiates a traffic flow. The destination node is selected randomly from the rest 48 nodes. The traffic load Tl varies from 5% to 60% of the channel rate.

Fig. 5.6 depicts the performance of PDP with various routing protocols under different traffic load. Since coordinated sleep scheduling is unrelated with PDP, hence we only compare the results of routing protocols with sleep scheduling. From Fig. 5.6, we can observe that the probability of packet errors at a receiver node becomes higher with an increase of traffic load due to the increased interference on average. Overall, EEOR has a higher probability of successful packet transmission than the other two routing protocols since it fully utilizes the advantage of WBA to create the multi-reception diversity. MHR

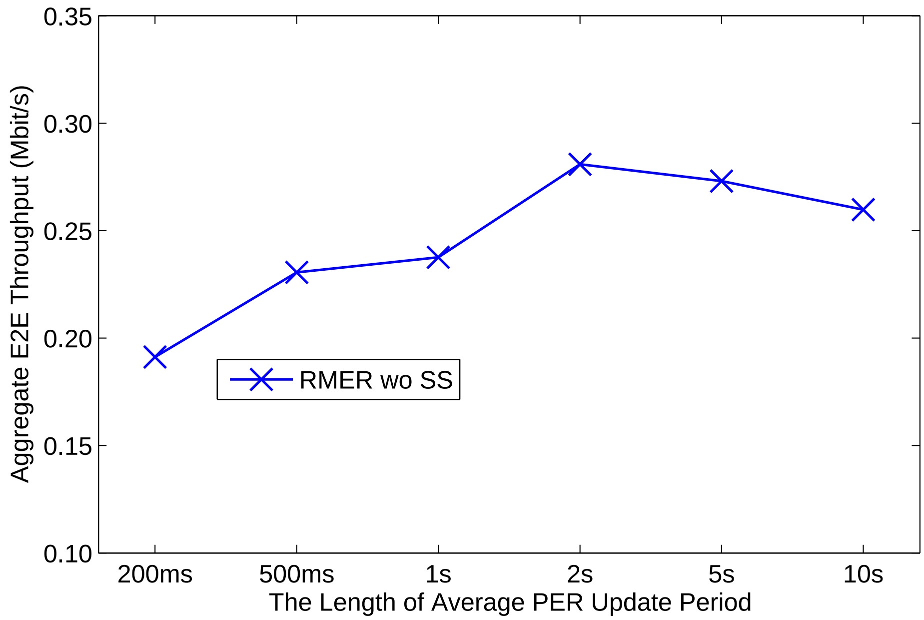

Figure 5.5: Comparison of the aggregate end-to-end throughput versus the length of average PER update period.

achieves the worst performance without the consideration of each individual link quality. RMER collects the information of PER over each outgoing link at a node thereby creating the chance of finding a path consisting of links with better quality. We observe that the gap between EEOR and other two routing protocols becomes larger when the traffic load is higher. The benefit of improving PDP is proportional to the traffic load. We make two cases as example to further demonstrate the trend as shown in Tables 5.3 and 5.4. From the results in both tables, we can see that RMER prefers to select the relay node with a shorter distance. Therefore the average number of hops connecting a pair of transmitter and receiver is increased compared with MHR. However, EEOR not only exploits the gain of multi-reception diversity to improve PDP at each hop, but also leverages the longest possible link for forwarding each packet. As a result, the average hop count required for EEOR is reduced, which on the contrary increases the end-to-end PDP.

Fig. 5.7 shows the performance of the total energy consumption when the traffic load varies. Overall, with the increase of the traffic load, all schemes generate increasingly higher total

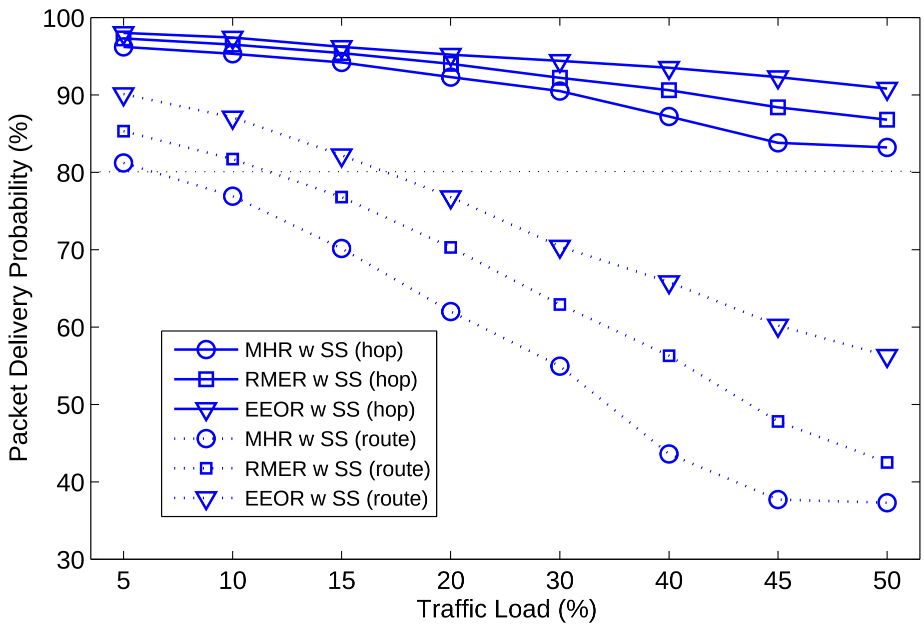

Figure 5.6: Comparison of the packet delivery probability versus the traffic load.

energy consumption. All the routing protocols without sleep scheduling consume more energy than those ones with sleep scheduling. The reason for the huge margin is that the energy wasted by idle listening is effectively saved with the use of sleep scheduling. Moreover, the margin becomes small as the increase of traffic load due to the reduced time in idle listening. In static wireless ad hoc networks, MHR wo SS has the poor performance because it tends to include wireless links between distant nodes. These long wireless links can be lossy, leading to energy waste caused by retransmissions. On the contrary, EEOR and RMER select better paths by explicitly taking into account the quality of wireless links. EEOR achieves the best performance as a result of the advantage of OR protocol. However, with the introduction of coordinated sleep scheduling, we are surprising to see EEOR does not always consume the least amount of energy. Note that EEOR w SS consumes more energy compared with other two schemes with sleep scheduling when the traffic load is high. The reason for that lies in two aspects. Firstly, more packets are sent by EEOR for a fixed duration of time thereby consuming more energy compared with the other two routing protocols. Secondly, it requires more neighboring nodes to overhear the

Table 5.3: Case a: traffic load = 10%.

Routing Protocol	Average Hop Count	PDP per hop	PDP per route
MHR	5.6	0.957	0.775
RMER	7.1	0.970	0.806
EEOR	6.6	0.981	0.881

Table 5.4: Case b: traffic load = 40%.

Routing Protocol	Average Hop Count	PDP per hop	PDP per route
MHR	6.1	0.882	0.465
RMER	6.9	0.916	0.549
EEOR	6.8	0.948	0.701

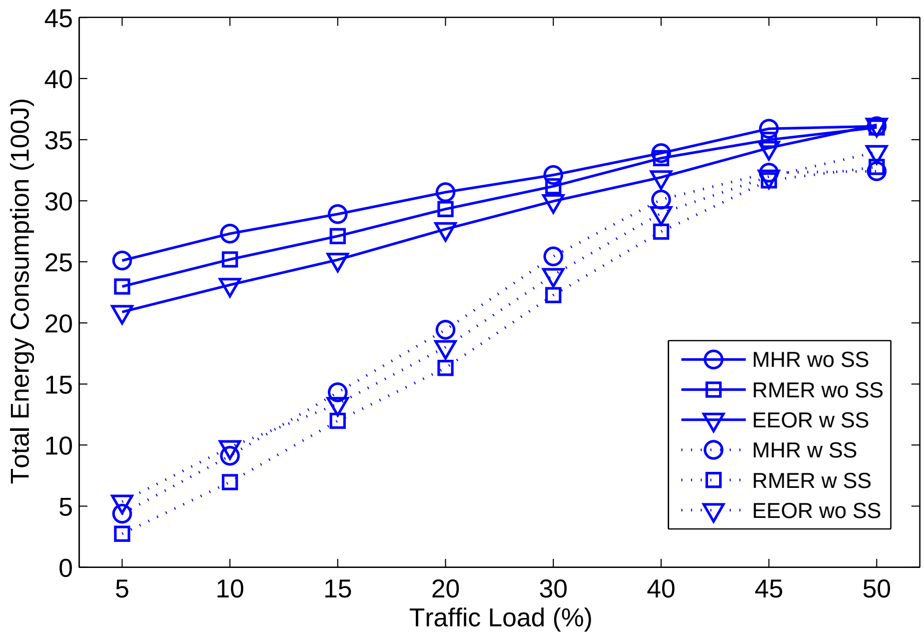

Figure 5.7: Comparison of the total energy consumption versus the traffic load.

data packet, which consumes more energy caused by overhearing. We will demonstrate this issue further to better understand the phenomenon.

The aggregate end-to-end throughput and packet delay performances are provided in Figs. 5.8 and 5.9. Similar to the results of PDP, EEOR achieves the best performances while MHR has the worst performance in terms of the throughput and delay. When the traffic load is increased to 50%, the network becomes congested and performances of the throughput of all routing protocols tend to be stable. EEOR achieves a higher throughput and lower delay due to the gains of multi-receiver diversity. It can distribute the total traffic load more equally than the other two routing protocols. The function of coordinated sleep scheduling causes some control packets overhead, but the performances loss is negligible, which reveal the effectiveness of the function of coordinated sleep scheduling.

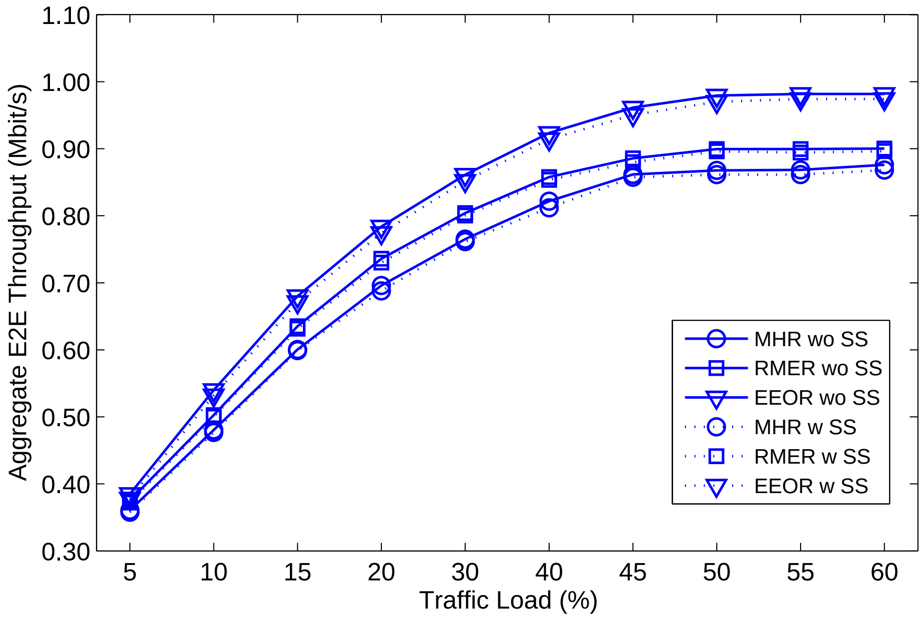

Figure 5.8: Comparison of the aggregate end-to-end throughput versus the traffic load.

Now we examine the performance of network-wide energy efficiency, where the simulation results are shown in Figs. 5.10 and 5.11. Fig. 5.10 illustrates the energy efficiency achieved by different routing protocols without sleep scheduling. As we can see, the energy consumption per packet of all routing protocols is monotonously decreased with the increase of traffic load. The reason for the trend is that the energy wasted in idle listening is reduced when the traffic load is high. EEOR does achieve the highest energy efficiency, corresponding to the current conclusions by existing work on OR protocols. The high energy efficiency is obtained by taking the advantage of multi-receiver diversity gain. In contrast to the conclusions obtained without the function of coordinated sleep scheduling,

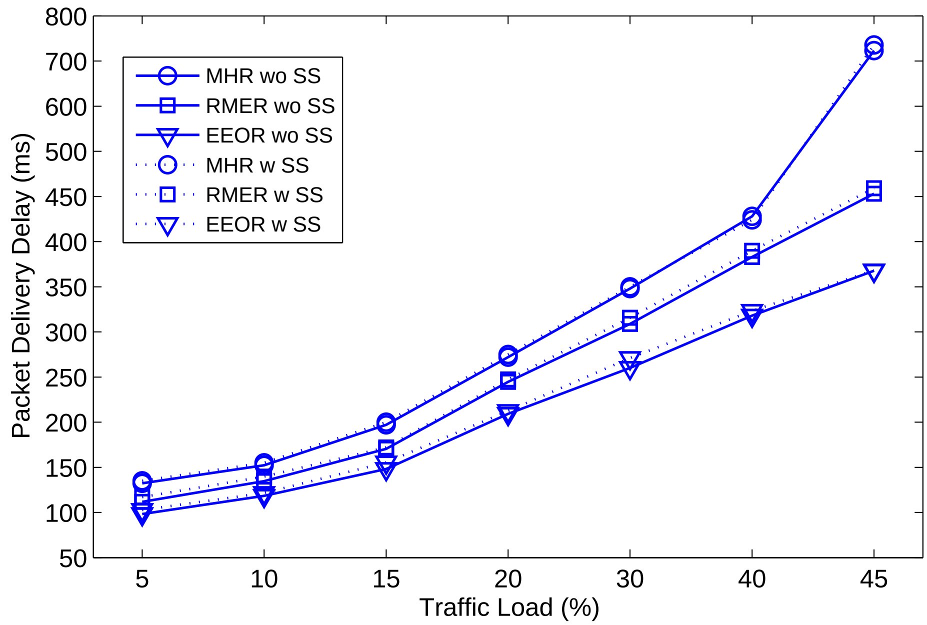

Figure 5.9: Comparison of the packet delivery delay versus the traffic load.

the performances of energy efficiency achieved by different routing protocols with sleep scheduling show different results. From Fig. 5.11, it is not intuitive that EEOR does not always achieve a better performance in term of energy efficiency. When the traffic load is relatively low, EEOR consumes more energy for each packet delivery since the increased energy consumed by potential forwarders overwhelms the saved energy at transmit nodes under good channel condition. Only under the condition that the packet loss occurs at higher probability, EEOR can have higher energy efficiency. Otherwise, RMER saves the most energy per packet instead. This conclusion contradicts the existing statement that OR protocols outperforms BPR protocols in terms of the energy efficiency. From another point of view, it verifies our identified problem in the motivation of Chapter 1. Thus we can reach a conclusion that the impact of coordinated sleep scheduling on the routing protocols depends on the traffic load over the wireless ad hoc networks.

Remark 1: The impact of coordinated sleep scheduling on the routing protocols depends on the traffic load over the wireless ad hoc networks. EEOR protocol achieves higher

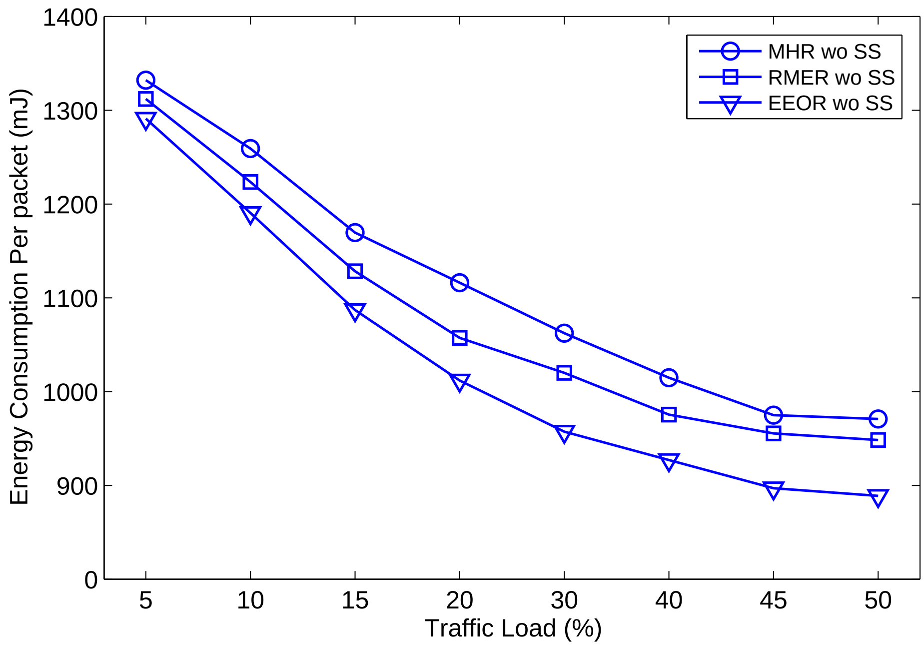

Figure 5.10: Comparison of the energy consumption per packet versus the traffic load under the use of routing protocols without sleep scheduling.

energy efficiency under high traffic load compared with RMER protocol when coordinated sleep scheduling is supported.

5.3.3 Impact of Node Density

Example 3: The maximum transmit power P_T is 100 mW, and totally we have four macro cells in the whole area as in the examples 1 and 2. The number of flows is always equal to the same proportion of 25% of the total number of nodes under different scenarios of the node density. The traffic load Tl is 40% and is kept the same in the example. The total number of nodes N changes from the minimum 52 to the maximum 112 with a step size of 12 nodes.

Fig. 5.12 shows the results of PDP with different routing protocols. We also summary the exact values of PDP at different point of node density in Tables 5.5- 5.7. Obviously,

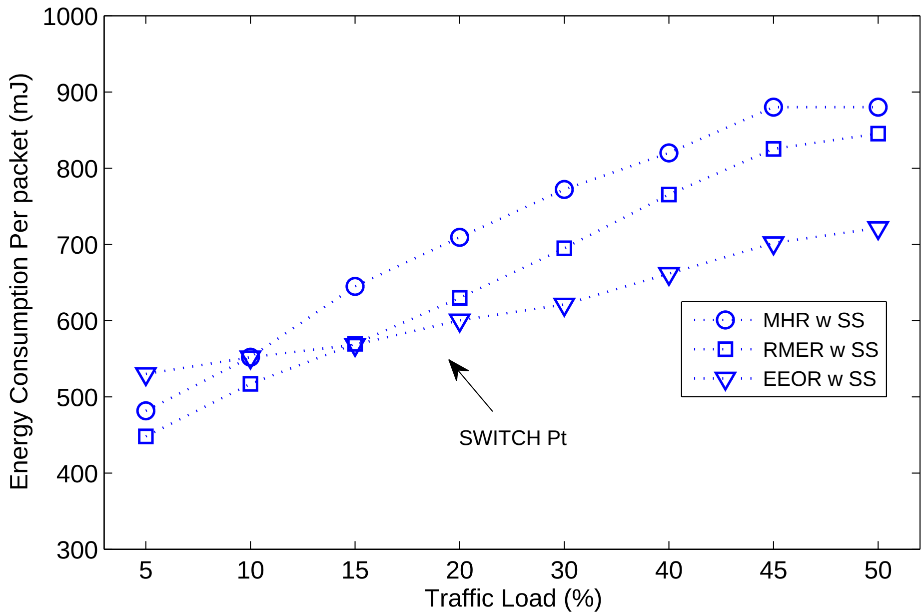

Figure 5.11: Comparison of the energy consumption per packet versus the traffic load under the use of routing protocols with sleep scheduling.

the performance of PDF achieved by MHR has nothing to do with the change in node density. It also reflects that the degree of interference on average is effectively controlled to almost the same under different scenarios. However, EEOR and RMER are sensitive to the node density. With an increase of node density, more links can be considered for route selection in those two routing protocols. EEOR outperforms RMER due to the fact that the improvement of PDP by OR protocol is more obvious than the BPR protocols. But when the number of available candidate nodes is increased to a certain extent, the PDP obtained by EEOR is not remarkably increased. The reason for that is due to the mathematic property of expression of successful transmission probability of OR protocol.

Fig. 5.13 shows the performances of total energy consumption obtained by different schemes. For those routing protocols without sleep scheduling, the total energy consumed over the network is increased with the number of total nodes due to increased overhearing energy waste. We can reach the same conclusion as in [6] that more energy would be wasted by overhearing when the node density is high. However, with the introduction of coordinated

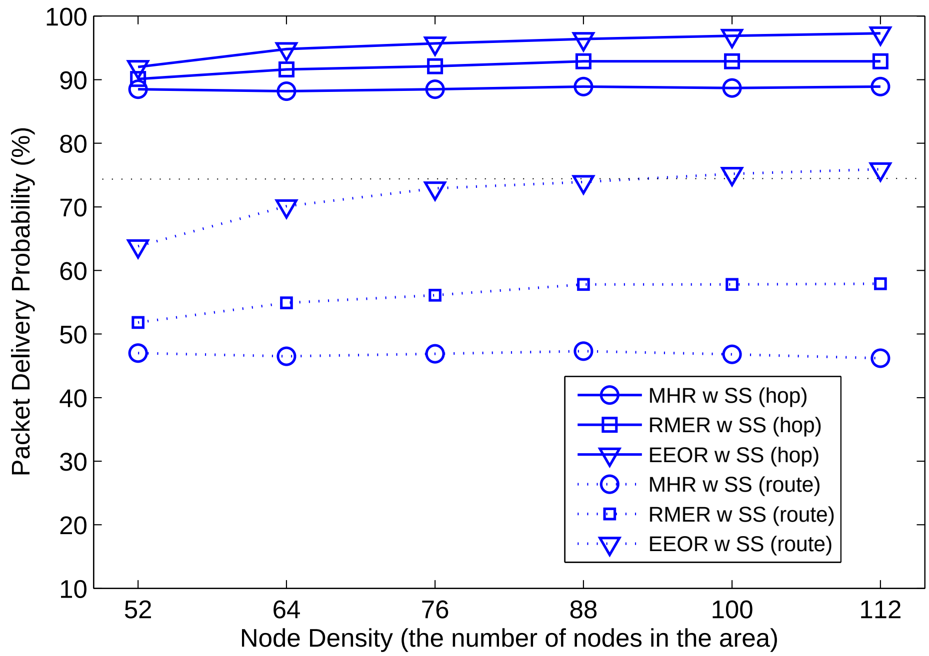

Figure 5.12: Comparison of the packet delivery probability versus the node density.

sleep scheduling, the amount of energy wasted by overhearing can be remarkably reduced. The total energy consumption of all routing protocols with coordinated sleep scheduling is hence decreased compared with those without sleep scheduling. However, EEOR consumes the most energy compared with other two schemes which contradicts the conclusion derived from the results when sleep scheduling is not supported. We can further observe that total energy consumption of EEOR is slightly increased with the increase of node density. The reason is that a larger signaling overhead is caused due to AC process.

The performance in terms of aggregate end-to-end throughput and packet delay are shown in Figs. 5.14 and 5.15. Similar to the results of performance comparison of PDP, EEOR can achieve higher throughput and lower packet delay compared with the other two routing protocols. It is worth to point that the average packet delay with three routing protocols is enlarged with the increase of node density. The main reason for that lies in the enlarged interval of TDMA frame, which causes a higher scheduling delay at each intermediate node. Overall, EEOR outperforms the other two routing protocols regardless of the function of

Table 5.5: Case c: node density = 52.

Routing Protocol	Average Hop Count	PDP per hop	PDP per route
MHR	6.1	0.883	0.469
RMER	6.3	0.901	0.518
EEOR	7.0	0.923	0.638

Table 5.6: Case d: node density = 64.

Routing Protocol	Average Hop Count	PDP per hop	PDP per route
MHR	6.1	0.882	0.465
RMER	6.9	0.916	0.549
EEOR	6.8	0.948	0.701

Table 5.7: Case e: node density = 88.

Routing Protocol	Average Hop Count	PDP per hop	PDP per route
MHR	6.1	0.884	0.470
RMER	7.1	0.921	0.553
EEOR	6.5	0.964	0.762

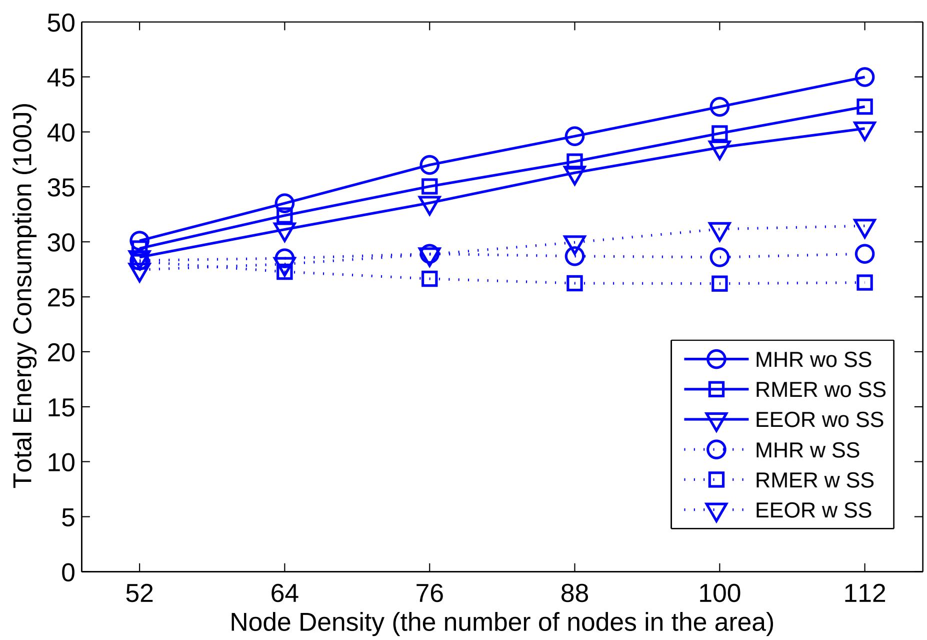

Figure 5.13: Comparison of the total energy consumption versus the node density.

coordinated sleep scheduling. The slight loss of performances with the introduction of sleep scheduling is resulted from the additional signaling overheard caused by coordinated sleep scheduling.

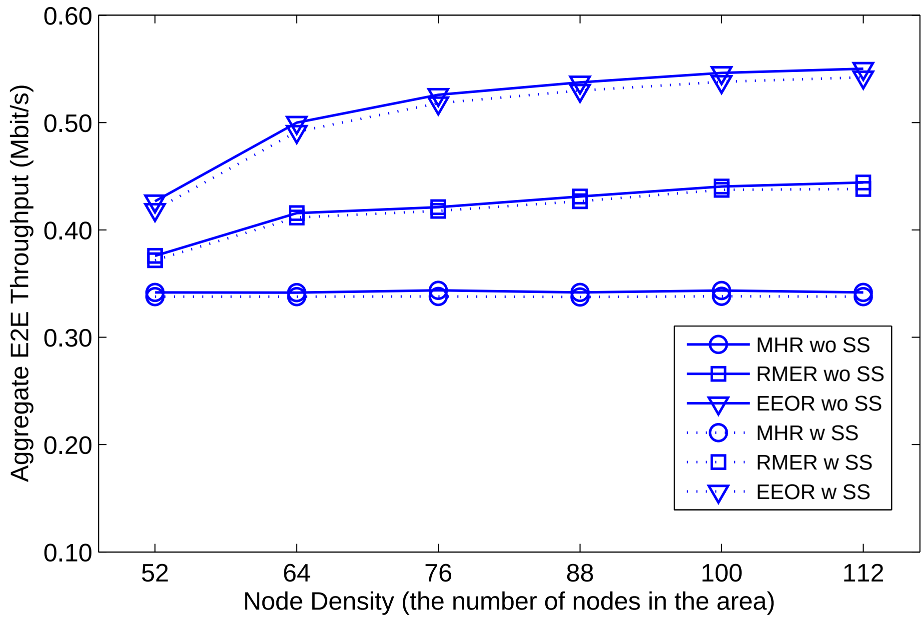

Figure 5.14: Comparison of the aggregate end-to-end throughput versus the node density.

Figs. 5.16 and 5.17 illustrate the results of performances in terms of energy efficiency obtained by different schemes. From Fig. 5.16, we can observe that network-wide energy efficiency using different routing protocols without sleep scheduling is decreased with the increase of node density. The reason for that is more energy would be wasted due to overhearing at uninvolved neighboring nodes. Moreover, EEOR can achieve the highest energy efficiency in term of energy consumption per packet compared with the other two routing protocols, which demonstrates the benefit of multi-receiver gains in OR protocol. Moreover, RMER outperforms MHR because RMER considers using the links with better quality. However, we notice that when the node density is relative high, such as 112, it seems EEOR takes no obvious advantage over RMER. The reason for that is mainly EE-OR requires a great number of neighboring nodes to receive the packet, which consumes more energy at those potential forwarders. The simulation results show that the benefit

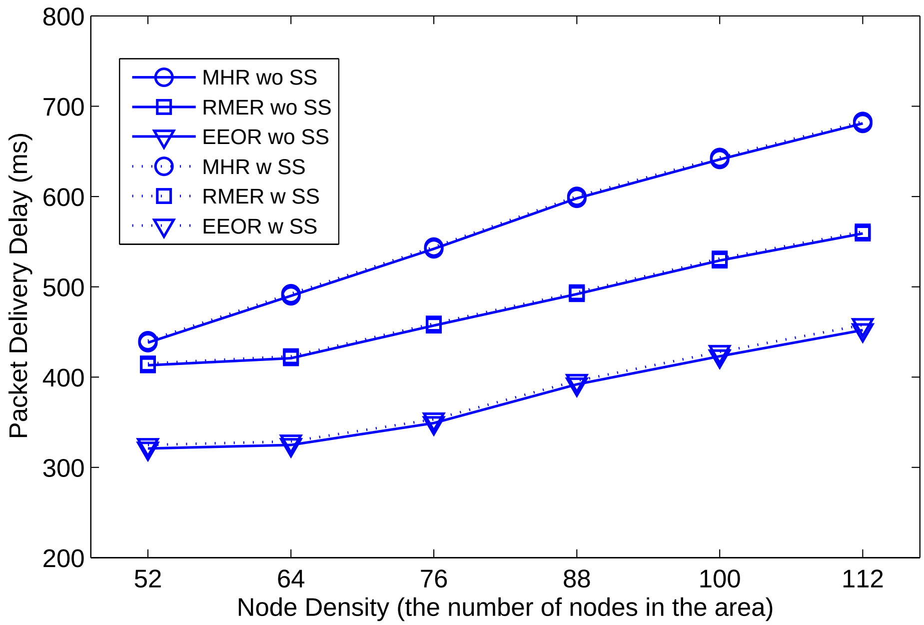

Figure 5.15: Comparison of the packet delivery delay versus the node density.

of energy efficiency achieved by EEOR is not proportional increased with the higher node density. Now, we compare the performance results of different routing protocols supporting coordinated sleep scheduling as shown in Fig. 5.17. It is interesting to observe that the energy efficiency obtained by EEOR is no longer monotonously increased with the number of nodes in the network. There is an optimal point for the highest energy efficiency regarding the different node density. When the node density is consistently increased beyond the optimal point, the benefit of energy saving achieved at transmitter nodes by EEOR cannot compensate the increased energy consumption at the forwarders. Consequently, EEOR can even obtain a lower energy efficiency compared with MHR until the limit of maximum candidate nodes is reached. From the results shown in those two figures, we can conclude that the performance of energy efficiency by EEOR is not increasingly improved with the increase of the node density. The impact of coordinated sleep scheduling is related with the node density in the network.

Remark 2: The impact of coordinated sleep scheduling is related with the node density in the network. There is an optimal point for the highest energy efficiency regarding different node density in the EEOR protocol when coordinated sleep scheduling is supported. Moreover, EEOR can even obtain a lower energy efficiency compared with RMER protocol when the node density is relatively high.

5.4 Summary

In this chapter, we present the simulation-based evaluation of different energy-efficient routing protocols with and without the function of coordinated sleep scheduling. We consider extensive system performance metrics based on the total energy consumption, throughput, and packet delay, as well as energy consumption per packet. The results show that coordinated sleep scheduling has an impact on the energy efficiency achieved by different routing protocols. First, we evaluate the impact of traffic load over the network on the overall performances. When the channel condition is relatively good as a result of the lower traffic load, the EEOR protocol cannot guarantee a higher energy efficiency as compared with the the MHR protocol. Then, evaluation of the node density impact on the overall performances shows that MHR even outperforms EEOR in term of energy efficiency in high node density scenario. Despite the improvement of packet delivery probability achieved by multi-receiver diversity gain in OR protocols, the effect of increased energy consumption at potential forwarders should be taken into account when coordinate sleep scheduling is supported.

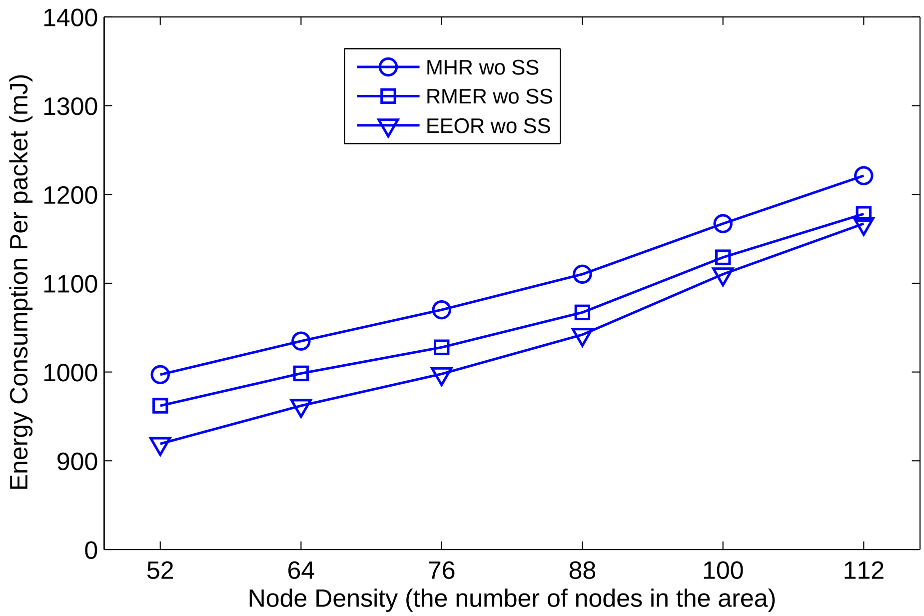

Figure 5.16: Comparison of the energy consumption per packet versus the node density under the use of routing protocols without sleep scheduling.

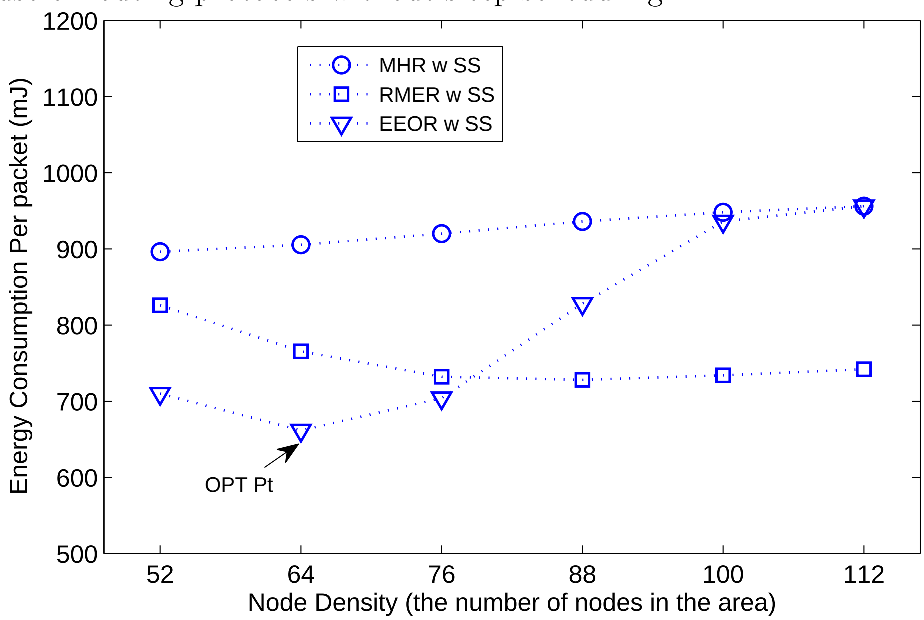

Figure 5.17: Comparison of the energy consumption per packet versus the node density under the use of routing protocols with sleep scheduling.

Chapter 6

Conclusions and Future Works

The performance of energy efficiency of the wireless ad hoc networks depends on several power-saving mechanisms. Two of the major mechanisms are energy-efficient routing and coordinated sleep scheduling in the network layer and link layer, respectively. From the perspective of reducing the network-wide energy consumptions, an efficient energy-efficient routing protocol should be capable of conserving more power on receivers, forwarders and even other uninvolved neighboring node besides the transmit power for a higher overall energy efficiency. This can be achieved by integrating the function of coordinated sleep scheduling into energy-efficient routing protocols, and taking into account the impact on different energy-efficient routing protocols. The aim of this thesis is to demonstrate the impact of coordinated scheduling on the overall performances using different energy-efficient routing protocols. We can summarize our research contributions as follows:

- We have proposed the framework of energy-efficient routing protocols supporting coordinated sleep scheduling to have the potential benefit of improving the energy efficiency. Extensive simulations shows that our framework can improve the overall system performance in terms of total energy consumption. Moreover, the quality of service (QoS) performance, such as throughput and delay, are almost unaffected by the coordinated sleep scheduling. In this way, the total network-wide energy efficiency will be effectively enhanced. To the best of our knowledge, we are the first to identify the impact of coordinated sleep scheduling on energy-efficient routing protocols.

- We have provided a comprehensive evaluation of how the traffic load affects the energy-efficient routing supporting coordinated sleep scheduling. It is shown that EEOR achieves higher energy efficiency under high traffic load where the channel condition becomes worse due to the increased interference. However, MHR outperforms EEOR under the situation of relatively good channel condition.
- Moreover, we have provided the evaluation of how the node density affects the overall system performance. We find out that there is an optimal point for maximizing the energy efficiency of EEOR with the introduction of coordinated sleep scheduling. When the node density is increased beyond the optimal point, the performance of energy efficiency achieved by EEOR is on the contrary degraded, resulting in a lower energy efficiency compared with RMER.

In this research, we focus on studying the impact of coordinated sleep scheduling on different energy-efficient routing protocols. Although this thesis provides a comprehensive study and evaluation from different perspectives, there are still some open issues that can be pursued to improve the performance of the energy-efficient routing supporting coordinated sleep scheduling in wireless ad hoc networks.

- **Performance evaluation under other network configurations**: In our work, we study the performance based on the adopted TDMA MAC protocol. CSMA-based MAC is another popular discussed and commonly adopted MAC scheme with different applications. However, collisions resulted from random access make it more difficult to conduct the performance evaluation. Moreover, a general network topology needs to be considered in the further research to reveal the effects of more network parameters.
- **Optimal design of EEOR protocol supporting coordinated sleep scheduling**: From the results obtained in our study, we can see that there is an optimal

point of maximizing the energy efficiency using EEOR. Therefore, the existing EE-OR protocol needs to be improved by determining the optimal forwarder list so as to achieve the optimal performance in terms of energy efficiency.

- **Cognitive energy-efficient routing protocol**: We have demonstrated the effects of network conditions on the actual system performance achieved by energy-efficient routing protocols. Therefore, we need to formulate the theoretical energy cost based on the observed network condition under the consideration of link layer and physical layer operations. It is envisioned to have the benefit of determining the optimal routing protocol at each node to maximize the network-wide energy efficiency. By incorporating the function of cognitively sensing the network condition in the routing decisions, each node can intelligently switch to the optimal energy-efficient routing protocol in order to improve the overall system performance.

APPENDICES

A.1: Algorithm of finding the optimal next-hop node in RMER

Algorithm 1 Algorithm of finding the optimal next-hop node in RMER

Input:

The neighboring nodes set of node u: $N(u)$
The expected cost of all the neighboring nodes of node u: $C_v^d, v \in N(u)$
The routing protocol: $rp = 0$
The destination node: d

Output:

Set $C_u^d(0, N(u), v^*) = 0$.
Set $C = \infty$.
for $(i = 1; i \leq |N(u)|; i = i + 1)$ **do**
    Compute $C_u^d(0, N(u), v_i)$ based on Equation 4.2.
    if $C_u^d(0, N(u), v_i) < C$ **then**
        Set $C_u^d(0, N(u), v_i) = C$.
        Set $v_i = v_i^*$.
    end if
end for
Return $C_u^d(0, N(u), v_i^*)$ and v_i^*.

A.2: Algorithm of finding the optimal forwarder list in EEOR

Algorithm 2 Algorithm of finding the optimal forwarder list in EEOR

Input:

The neighboring nodes set of node u: $N(u)$
The expected cost of all the neighboring nodes of node u: $C_v^d, v \in N(u)$
The maximum number of candidate: C_m
The routing protocol: $rp = 1$
The destination node: d

Output:

Set $C_u^d(1, N(u), Fwd^*) = 0$.
Set $Fwd^* = \phi$.
Set $\widehat{Fwd} = N(u)$.
Set $C = \infty$.
Set $M = \infty$.
while $Fwd^* < C_m$ **do**
    Set $cand = \arg\min_{v_i \in \widehat{Fwd}} C_u^d(1, N(u), Fwd^* \cup v_i)$ based on Equation 4.7 .
    Set $C = C_u^d(1, N(u), Fwd^* \cup v_i)$.
    if $C < M$ **then**
        Set $Fwd^* = Fwd^* \cup v_i$.
        Set $M = C$.
    else
        Set $C_u^d(1, N(u), Fwd^*) = M$.
        Break;
    end if
end while
Return $C_u^d(1, N(u), Fwd^*)$ and Fwd^*.

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