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Energy-efficient routing over coordinated sleep scheduling in wireless ad hoc networks

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Abstract In this paper, we study how energy-efficient routing at the network layer can be coordinated with sleep scheduling at the link layer to increase network-wide energy efficiency in wireless ad hoc networks. We identify a trade-off between the reduced transmit power at senders with multi-receiver diversity and the increased receive power at forwarders with coordinated sleep scheduling. Moreover, we provide a comprehensive study of how coordinated sleep scheduling affects the energy-efficient routing performance based on a 2-D gird topology and time division multiple access (TDMA) medium access control (MAC). Simulation results demonstrate the effectiveness of the integrated routing and sleep scheduling, significant impact of coordinated sleep scheduling on the energy-efficient routing performance, and relationship between networking conditions (in terms of the traffic load and node density) and overall system performance achieved by different energy-efficient routing protocols.

Keywords Energy-efficient routing · Coordinated sleep scheduling · Energy efficiency · Performance evaluation · Wireless ad hoc network

1 Introduction

Recent advances in wireless communication systems have opened up opportunities of ubiquitous communication network coverage. Wireless ad hoc networking is becoming increasingly popular as it enables a collection of wireless devices to form a network independently of any fixed infrastructure. However, many small-sized wireless devices such as smartphones and tablets have limited operation time due to the battery power supplies. Experiment results have shown that the radio interface is a major source of power consumption at a wireless ad hoc node [1].

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Therefore, considerable efforts have been devoted to the design of power-saving protocols over the radio interface.

Normally, the radio interface hardware at a node can operate in four different modes: transmit, receive, idle and sleep. The transmit mode consumes the highest power while the sleep mode only consumes very little power. The power consumed in the idle mode is comparable with that in the receive mode because the radio interface must be up and ready to receive any possible traffic [2]. For wireless ad hoc networks, there are mainly three sources of non-essential energy expenditure [3]. The first source is packet transmission collisions as a result of random access. When a transmitted packet is corrupted due to collisions, retransmissions of the packet consume extra energy. The second source is idle listening, which corresponds to the energy consumed in the idle mode. When the traffic load over a network is relatively low, it is a dominant factor of energy waste. In a wireless network, a packet transmission can be overheard by many neighbors of the transmitter. These nodes consume energy in overhearing packet transmissions unnecessarily as the packets are not intended for them [4].

Researchers have developed sleep scheduling to reduce energy wasted in idle listening and overhearing by turning off the radio interface in a controlled fashion [5]. However, it suffers from higher data delivery delay and lower network throughput. Generally, coordinated sleep scheduling approaches can potentially achieve better performance with centralized coordination of sleep schedules than with random sleep scheduling [6]. Meanwhile, energy-efficient routing is proposed to reduce the end-to-end transmission energy cost of data communication. Various factors such as ambient noise, fading and transmission interference can lead to packet losses due to transmission errors over wireless medium. Therefore, a retransmission mechanism is commonly employed to recover from packet losses. Energy-efficient reliable protocols that accommodate the potential retransmissions are first proposed to find the most energy-efficient path connecting the pair of source and destination. Opportunistic routing (OR) (also called anypath routing) has recently overturned this principle of best path routing (BPR) by allowing multiple forwarders to opportunistically deliver packets to the destination accounting for their time-variant channel conditions. It leverages the wireless broadcast advantage (WBA) to mitigate the impact of packet losses: The packet transmission from 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 next-hop. It is shown that OR can achieve higher energy efficiency than BPR [7,8].

By and large, existing energy-efficient routing protocols focus on controlling the transmit power of the radio interface. Although significant in terms of reducing the power consumption of a sender, it does little to conserve the power among other nodes such as receivers and forwarders. Therefore, energy-efficient routing which supports coordinated sleep scheduling has the potential benefit of higher network-wide energy efficiency. Nevertheless, the function of coordinated sleep scheduling exerts an influence on the actual energy-efficient routing performance. On one hand, increasing the number of potential forwarders by OR protocols reduces the transmit power at a sender. On the other hand, it reduces the opportunities of powering off the radio interface at those forwarders as 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 reception at those forwarders.

Therefore, energy savings achieved by the routing protocols should be revisited with the introduction of coordinated sleep scheduling. Moreover, OR protocols need to be analyzed in terms of energy efficiency in comparison with BPR protocols. To the best of our knowledge, this paper is the first study of the impact of coordinated sleep scheduling on energy-efficient routing performance. By doing this, our results shed some light on how to improve network-wide energy efficiency with the energy-efficient routing protocols in wireless ad hoc networks. The contributions of this paper are in two aspects:

1. We present a framework of energy-efficient routing to support coordinated sleep scheduling which can accommodate both BPR and OR protocols for fair performance evaluation.
2. We provide comprehensive performance evaluations to study the performance comparison under different networking conditions. Through simulations, we study the effects of network parameters (in terms of the traffic load and node density) on the actual system performance achieved by BPR and OR protocols respectively.

The rest of this paper is organized as follows. Section 2 reviews background and some related works. Section 3 describes the system model. In Section 4, we present the proposed framework of energy-efficient routing supporting coordinated sleep scheduling. The results of performance evaluation are given in Section 5. Finally, Section 6 concludes this research.

2 Background and related work

In this section, we review some existing power-saving protocols with respect to sleep scheduling and energy-efficient routing in wireless ad hoc networks.

2.1 Sleep scheduling in wireless ad hoc networks

There is extensive literature on sleep scheduling in wireless networks. The proposed protocols range from random sleep scheduling approaches to more intelligent coordinated sleep scheduling. Random sleep scheduling lets each node to decide its own sleep schedule. However, it introduces latency for waiting for a receiver to wake up since the sender and receiver are usually not scheduled to be active concurrently [9]. In coordinated sleep scheduling mechanisms, a common active period can be coordinated by broadcasting sleep schedules to neighbors so that the waiting time can be greatly decreased [5]. For instance, the IEEE 802.11 has defined a power saving mode (PSM) [10]. In the PSM, time is divided into periodic beacon intervals. At the beginning of each beacon interval, all nodes are required to stay awake for a period called 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 power off the radio interface for energy saving. Based on the similar idea, S-MAC [3] and R-MAC [11] are proposed for multi-hop transmissions with the purpose of reducing the end-to-end delay. Coordinated sleep scheduling is more appropriate for supporting multimedia traffic with delay and throughput requirements.

2.2 Energy-efficient routing in wireless ad hoc networks

Over the past decade, energy-efficient routing has been widely studied to conserve power from the perspective of network layer. Early power-aware routing protocols that minimize the total transmit power based on the characteristic of transmission attenuation are no longer suitable for practical wireless networks with lossy links [12]. Therefore, energy-efficient reliable routing and opportunistic routing are developed, considering the effect of channel unreliability on energy consumption.

Minimum total reliable transmission power protocol (MTRTP) in [13] and reliable minimum energy routing (RMER) protocol in [8] both emphasize reliable transmission energy cost based on a retransmission system. They exlopit the information of packet error rate (PER) over each wireless link to find the optimal route requiring the least amount of energy. RMER further addresses the practical limitation of the maximum allowable number of retransmissions into the formulation of energy cost. It is worth to mention that above BPR protocols all follow a conventional design principle of traditional wired network: the best routes are predetermined before data transmissions and all data flows from the source and destination follow the routes.

On the contrary, OR allows each node to select a prioritized forwarder list consisting of multiple candidates to deliver a packet to the destination. After each transmission attempt of the packet, the forwarder with the highest priority that successfully received it will be chosen as the next-hop node. Compared to the BPR protocols, the deferred choice gives opportunities to reduce the number of retransmissions so that more transmit power can be saved. One fundamental challenge is how to optimize the forwarder list and assign the priority to each potential forwarder for maximizing the network performances. The extreme opportunistic routing (ExOR) protocol in [7] is considered as one of the earliest works on OR. The candidates forward a 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. 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. Zhong et al. [14] proposes the concept of expected anypath transmissions (EAX) which captures not only the ETX for successfully transmitting a packet from the source to at least one candidate, but also the ETX for forwarding the packet in turn to the destination. Thus EAX indicates the extent of gain possible with OR over BPR. Considering that EAX-based protocols do not provide any proof of optimality, a least cost anypath routing (LCAR) protocol is proposed to compute the optimal forwarders [15]. Though EAX can represent the energy consumption during the packet delivery, the energy-efficient opportunistic routing (EEOR) protocol specially focuses on the minimization of total transmission energy in OR [16]. It first calculates the expected energy cost and then chooses the forwarder list such that the total transmission energy is minimized. Simulation results demonstrate that EEOR protocol outperforms ExOR and existing BPR protocols in terms of energy efficiency and throughput.

In the following, we propose a framework of energy-efficient routing protocols supporting coordinated sleep scheduling, which can facilitate the operations of existing energy-efficient routing protocols with principles of BPR and OR, respectively. Moreover, we investigate the impact of coordinated sleep scheduling on energy-efficient routing performance. Simulations results demonstrate the proposed framework provides a substantially higher network-wide energy efficiency than existing energy-efficient routing protocols. In addition, different network parameters (e.g., traffic load and node density) have a significant effect on the overall routing performance.

3 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 stationary and share a common radio channel. The multi-hop wireless network is modeled by a communication graph $G = (V, E)$ where V is the set of nodes and E is the set of directed links. 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. The source-destination pairs (S, D) are given, where S and D denote the set of source and destination nodes, respectively. We assume that wireless link gains are independent and denote the average PER as $P_{u,v}^{error}(x)$ for link (u, v), which is the probability that a transmission of data packet of size x bits over the link (u, v) is not successful. All the nodes support adjustable transmission power, but the transmission rate does not change with the transmit power. The transmit power $P_t(u)$ at node u belongs to a finite set of transmit power levels, denoted as $S(u) = \{P_t^1(u), P_t^2(u), ..., P_t^m(u)\}$, where m represents the number of allowable transmit power levels at each node. We define $N(u)$ as the neighboring node set of node u. Specifically, the transmit power $P_t(u)$ in BPR protocols is represented by the minimum transmission power from the discrete set of $S(u)$ over wireless link (u, v) that satisfies the targeted link error rate T_h. The transmit power $P_t(u)$ in OR protocols is the minimum power required for transmission from node u to the farthest forwarder node at node u from $S(u)$.

3.2 Link layer

Consider a time-slotted system, all the nodes are synchronized with the aid of global position system (GPS) device. We adopt a sender-based TDMA protocol to minimize the influence of collisions on the actual energy cost from the link layer. Generally, the TDMA schedule is determined according to the interference models such as the protocol interference model and physical interference model [17]. Consider node u_i transmits over the channel to receiver v_i. This transmission can be permitted if the following conditions are satisfied for every other node u_j simultaneously transmitting over the channel:

1) **Protocol interference model:**

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

where the parameter σ models the guard zone specified by the protocol to prevent a neighboring node from transmitting at the same time;

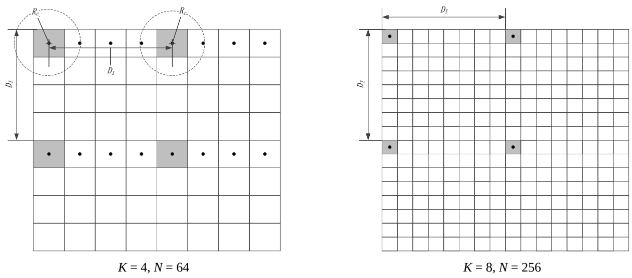

Fig. 1 An illustration of restricted TDMA MAC under different node density scenarios with $K = 16$ and $K = 64$, respectively. The dots at the center of each cell represent nodes, and grey cells can transmit simultaneously.

2) **Physical interference model:**

$$\frac{P_T \cdot A|u_i - v_i|^{-\alpha}}{N_0 + \sum_{j \neq i} P_T |u_j - v_i|^{-\alpha}} \geq \beta \qquad (2)$$

where N_0 denotes the ambient noise power level, α and A denote the parameters of the propagation channel model, and P_T denotes the maximum transmit power at each transmit node. The threshold of signal to interference plus noise ratio (SINR) β in a fading environment is usually specified in such a way that T_h is satisfied for reliable transmission.

We can directly conclude from [6,17] that, if each transmission is limited to communicate within a communication range of R_c with the maximum transmit power P_T, simultaneous transmissions can take place among links that are at least D_I away without violating aforementioned interference models. The value of R_c is determined by the parameters in the interference models (e.g., $\sigma, N_0, P_T, A, \alpha, \beta$). We group a block of K cells within a square with size $D_I \times D_I$ into a macro-cell as shown in Fig. 1. Each node is allocated with a unique time slot from a sequence of K successive slot, i.e., the length of one TDMA frame is equal to K slots. By doing this, we can use the round-robin scheduling on all macro cells in each time slot, such that transmitting cells (in dark) that are always D_I away can transmit data simultaneously, while satisfying the requirement of T_h of the system.

Consider truncated hop-by-hop retransmission, in this mechanism, a lost data packet is retransmitted by the sender node at each hop. An acknowledgement (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 Q_m of transmission attempts is reached. The packet will be dropped by the sender if it cannot be successfully delivered within the maximum number of attempts.

3.3 Physical layer

Consider an single input single output (SISO) system, where each transmitter uses a standard transmission scheme specified in IEEE 802.11g [10] consisting of quadrature phase shift keying (QPSK) and convolutional code with coding rate 3/4. 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.

To capture the effect of a propagation environment on a radio signal, we consider the free-space path loss model, augmented by a Rayleigh fading as presented in [18, 19]. The channel is characterized by a slow, flat fading, i.e., the channel remains invariant over the period of a time slot, but it varies from slot to slot. The channel quality is captured by the received SNR γ per slot which is a random variable with the probability density function (PDF) given by

$$p_\gamma(\gamma) = \frac{1}{\bar{\gamma}}\, e^{\frac{\gamma}{\bar{\gamma}}} \tag{3}$$

where $\bar{\gamma} = E(\gamma)$ is the average received SNR at the receiver. According to the Friis formula [20], $\bar{\gamma}$ is related to the free-space path loss model, given by

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

where $l_{u,v}$ is the distance between a pair of transmitter and receiver (u, v), P_R is the received signal power, 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. Thus the channel parameters in the physical interference model $A = \frac{G_t G_r c^2}{(4\pi)^2 f_1 f_c^2}$.

4 Energy-efficient routing supporting coordinated sleep scheduling

In this section, we present our proposed framework of energy-efficient routing which supports coordinated sleep scheduling. At first, we elaborate how the function of coordinated sleep scheduling is integrated into the MAC protocol. Then, we present the minimum hop routing (MHR), RMER and EEOR used as energy-efficient routing protocols in our performance evaluation.

4.1 Coordinated sleep scheduling

In our 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 where transmitters with the communication demand send a signaling packet of traffic indicator to inform its intended receiver nodes. During the DATA period, 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. Fig. 2 uses an example to illustrate the sleep scheduling combined with OR and BPR

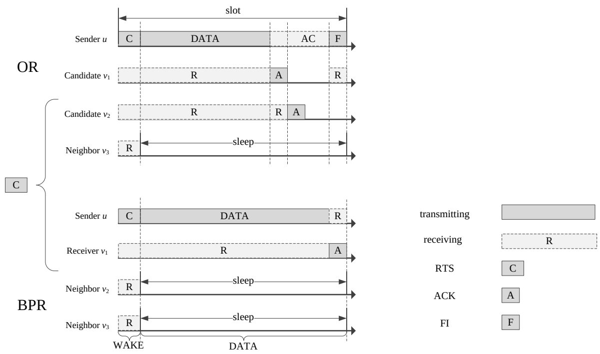

Fig. 2 An illustration of the routing operation within a single time slot

routing operations, respectively. Suppose in this time slot, sender node u has data to transmit and v_1, v_2, v_3 are three neighbor nodes within its transmission range.

In the 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} for the different routing protocols, and all the nodes within its transmission range, i.e., v_1, v_2, v_3, 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. In the DATA period, a data packet with packet length L_{DATA} is transmitted during this period. The routing operation varies with respect to BPR and OR protocols:

1) **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 interface 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;

2) **OR packet transmission:** Sender u multicasts the data packet to the multiple candidate nodes specified in the forwarder list $\eta(u) = \{v_1, v_2\}$. Node v_3 turns off the radio interface to enter the sleep mode. Here we introduce a TDMA-like approach in the ACK coordination (AC) period for the OR protocols based on [21]. 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 final indication (FI) message that indicates node v_1 to take the responsibility of forwarding the data 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 considered for practical applications.

We assume that signaling packets with a small packet length are not subject to transmission errors while data packet in general encounter link failures as in [21]. This assumption is made only for simplifying the calculation of energy cost in the following.

4.2 Energy-efficient routing protocols

1) **MHR:** The MHR protocol uses the route metric of hop count where the link quality for this metric is a binary concept, i.e., either the link exists or it does not [22]. There is a link from u to v, if the PER over the link satisfies the targeted link error rate.

2) **RMER:** Due to the limit of the maximum number of retransmissions, a data packet can be retransmitted a random number of times not greater than Q_m. Let $E[rp, L_{DATA}, Q_m]$ be the expected number of times that sender u needs to transmit a packet of length L_{DATA} 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 $E[0, L_{DATA}, Q_m]$ and PER is obtained according to Appendix A in work [8], given by

$$E[0, L_{DATA}, Q_m] = \frac{1 - P_{u,v}^{error}(L_{DATA})^{Q_m}}{1 - P_{u,v}^{error}(L_{DATA})}. \tag{5}$$

Here we define $C_u^d(rp, N(u), v)$ as the expected total energy cost of sending one data packet from node u to node v for a flow with destination node d when routing protocol rp is used. The energy cost of a link in the RMER protocol is the total amount of energy consumed in the transmitter and the receiver nodes to exchange a data packet. Denote the expected total energy cost at node v by C_v^d, the total power consumption at the transmitter and receiver by P_{tr} and P_{rc}, respectively. According to [8], $C_u^d(0, N(u), v)$ can be written as

$$C_u^d(0, N(u), v) = E[0, L_{DATA}, Q_m]\frac{L_{DATA}}{R}(P_{tr}+P_{rc})+\frac{L_{ACK}}{R}(P_{tr}+P_{rc})+C_v^d. \tag{6}$$

We adopt the well-known Bellman-Ford algorithm for the RMER protocol to determine the optimal next-hop node v_i^* as shown in Algorithm 1.

3) **EEOR:** Let ρ denote the probability that a data packet sent by node u is received by at least one node in the forwarder list $\eta(u)$. Then, we can obtain that $\rho = 1 - \prod_{v_i}^{|\eta|} P_{u,v_i}^{error}(L_{DATA})$. The expected transmission count $E[1, L_{DATA}, Q_m]$ can be derived as

$$E[1, L_{DATA}, Q_m] = \frac{1 - \rho^{Q_m}}{1 - \rho}. \tag{7}$$

Define the expected energy cost at node u as $C_u^d(1, N(u), \eta)$ 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., $\eta(u) = \{v_1, v_2, ..., v_{|\eta|}\}$, where $i < j$ for $C_{v_i}^d < C_{v_j}^d$. The communication cost for agreement in the AC period is omitted, and the expected energy mainly consists of two parts. Let

Algorithm 1 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 (6).
  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^*.

$C_u^s(d, \eta)$ 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 η. According to [16], it is given by

$$C_u^s(d, \eta) = E[1, L_{DATA}, Q_m] P_{tr} \frac{L_{DATA}}{R}. \tag{8}$$

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 to the destination, which is denoted by $C_u^f(d, \eta)$. 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 η, the probability that node v_1 forwards the packet is $1 - P_{u,v_1}^{error}$ and the expected cost of v_1 is $C_{v_1}^d$. Then, node v_2 will forward the packet with probability $P_{u,v_1}^{error}(1 - P_{u,v_2}^{error})$ and the cost is $C_{v_2}^d$. Basically, node v_i forwards the packet if it receives the packet and node v_j, $0 < j < i$, did not receive the packet, in which the cost is $C_{v_j}^d$. As a result, the aforementioned process of calculation is repeated until every possible outcome of packet reception at all the nodes within the forwarder list is considered. Hence, the expected forwarding energy cost can be computed as

$$B = (1 - P_{u,v_1}^{error}(L_{DATA}))C_{v_1}^d + \sum_{i=2}^{|\eta|} (\prod_{j=1}^{i-1} P_{u,v_j}^{error}(L_{DATA})(1 - P_{u,v_i}^{error}(L_{DATA}))C_{v_i}^d). \tag{9}$$

Since B is obtained under the condition that at least one forwarder in the forwarder list receives the packet, we can compute $C_u^f(d, \eta)$ by

$$C_u^f(d, \eta) = B \times E[1, L_{DATA}, Q_m]. \tag{10}$$

Overall, the expected cost of data transmission is given by

$$C_u^d(1, N(u), \eta) = C_u^s(d, \eta) + C_u^f(d, \eta). \tag{11}$$

The distributed algorithm of finding the optimal forwarder list η^* is shown in Algorithm 2, and its optimality is proved in [15].

Algorithm 2 The optimal forwarder list in EEOR

Require:

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

Ensure:

Set $\eta^* = \phi$.
Set $C_u^d(1, N(u), \eta^*) = 0$.
Set $\widehat{\eta} = N(u)$.
Set $C = \infty$.
Set $M = \infty$.
while $\eta^* < C_m$ **do**
    Set $cand = \arg\min_{v_i \in \widehat{\eta}} C_u^d(1, N(u), \eta^* \cup v_i)$ based on Equation (11).
    Set $C = C_u^d(1, N(u), \eta^* \cup v_i)$.
    if $C < M$ **then**
        Set $\eta^* = \eta^* \cup v_i$.
        Set $M = C$.
    else
        Set $C_u^d(1, N(u), \eta^*) = M$.
        Break;
    end if
end while
Return $C_u^d(1, N(u), \eta^*)$ and η^*.

5 Performance evaluation

5.1 Simulation setup

To evaluate the impact of coordinated sleep scheduling, we implement 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 (hereafter referred to as w SS/wo SS). We choose four performance metrics in terms of the packet delivery probability (the ratio of successful received packets over the total number of packets sent at each hop or along a route), total energy consumption, aggregate end-to-end throughput and energy consumption per packet. We investigate the impacts of the following network parameters: 1) Traffic load, defined as the aggregate payload data arrival rate at source nodes, which is denoted as the proportion T_l of the channel rate R; 2) Node density, defined as the total number of nodes N located in the same area.

The traffic load is equally distributed among all the source nodes on average, and packets are generated at each source node according to a Poisson process. Each simulation run lasts for 200 seconds and each result is obtained from the average of 50 runs. We consider the commonly adopted power consumption model as in [8] where the power consumption related to a packet transmission is abstracted into fixed circuit power to run the transceiver circuitry and scalable power consumed by the transmit power amplifier. Let A_u denote 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. Then, we can get $P_{rc} = B_v$ and $P_{tr} = A_u + \frac{P_t(u)}{\kappa_u}$.

Table 1 Values of fixed parameters related to energy consumption used in simulations

Parameter	Value
Network area	$400 \times 400m^2$
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
Maximum number of transmissions (Q_m)	3
Maximum number of candidates (C_m)	6
Targeted packet error rate (T_h)	0.2
Data packet size (L_{DATA})	1080 byte
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

The specific power-related parameters can be obtained based on the datasheet of Cisco Aironet [23] and above equations. Overall, the values of fixed parameters used in the simulations are listed in Table 1.

5.2 Simulation methodology

There have been great efforts to model the successful packet reception over a wireless link. Most of existing works adopt a deterministic reception model that the packet is successfully received when the strength of received SINR is above a threshold [8]. However, in practical wireless communication systems, packet errors for coded transmissions are no longer independent with each other. To simplify the simulation of the physical layer, we adopt the SINR-based approach to model the packet receptions. Each successful packet reception follows the probability of successful packet reception based on the value of received SINR. We follow the approach of [18] for fitting a polynomial to the exact PER versus received SINR γ obtained from practical simulations. The approximate instantaneous PER over the link (u, v) is described as

$$\varepsilon_{u,v}(\gamma) = \begin{cases} 1, & 0 < \gamma < \gamma_p \\ a \cdot e^{-b \cdot \gamma}, & \gamma \geq \gamma_p \end{cases} \tag{12}$$

where we obtain 67.6181, 1.6883 and 3.9722 (dB) for parameters of a, b and γ_p directly from the results in [18] regarding our transmission scheme and L_d.

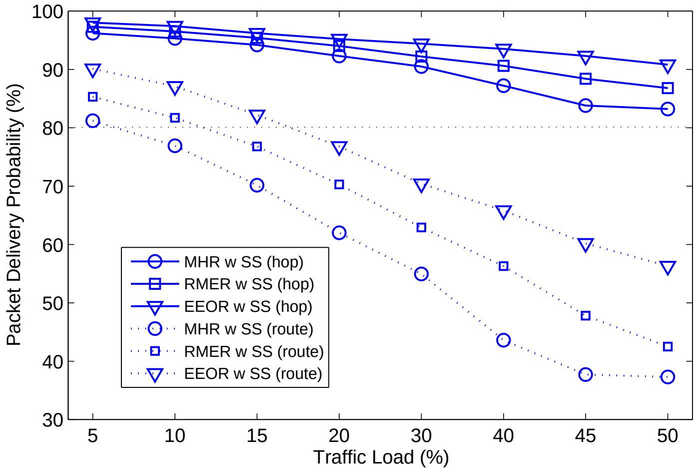

Fig. 3 The packet delivery probability versus the traffic load

In the link layer model described in Section 3.2, the TDMA schedule depends on the SINR threshold β specified in the physical interference model for a given T_h. We modify the approach as suggested in [18] to model the relation between β and T_h. Taking expectations over Rayleigh channel randomness, the average PER for a given value of average SINR is as follows:

$$P_{u,v}^{error} = \int_0^\infty \varepsilon_{u,v}(\gamma) \cdot p_\gamma(\gamma) d\gamma = \int_0^{\gamma_p} p_\gamma(\gamma) d\gamma + \int_{\gamma_p}^\infty a \cdot e^{-b\gamma} p_\gamma(\gamma) d\gamma. \quad (13)$$

Therefore, we can obtain the theoretical value of β according to Equations (2-4, 13) for the given T_h. Note that the average SINR here is regarded as the worst-case SINR, which does not account for the randomness of interfering sources, so the requirement of T_h can be fully ensured. To estimate the average PER more accurately, we resort to the measurement-based approaches proposed in [24] where each node measures the packet errors using observed interference locally and reports the estimated average PER to each sender periodically. In our simulations, we all set the update interval to be 2 second.

5.3 Simulation Results

5.3.1 Impact of traffic load

Network Scenario: The maximum transmit power P_T is 100 mW, the total number of nodes N is 64, so we have four macro cells in the whole area. We randomly select 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 T_l varies from 5% to 60% of the channel rate.

A. Packet delivery probability

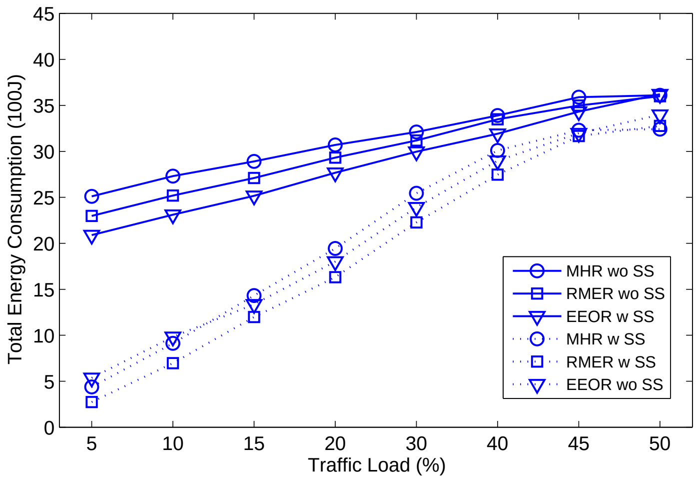

Fig. 4 Total energy consumption versus the traffic load

Fig. 3 depicts the performance of packet delivery probability with various routing protocols versus different traffic load. 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, MHR has the worst performance without the consideration of diverse link quality. RMER collects the information of PER thereby creating chances of finding a path consisting of links with better quality. EEOR outperforms the other protocols since it not only exploits the gain of multi-reception diversity to improve packet delivery probability 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 increases the end-to-end packet delivery probability. The gap between EEOR and others becomes larger when the traffic load is higher.

B. Total energy consumption

Fig. 4 shows the performance of total energy consumption when the traffic load varies. Overall, with an increase of the traffic load, all schemes have increasingly higher total energy consumption. All the routing protocols without sleep scheduling consume more energy than those which with sleep scheduling. The larger energy consumption gap comes from the energy wasted by idle listening, which is effectively reduced by sleep scheduling. The gap becomes smaller as the traffic load increases due to the reduced time in idle listening. MHR wo SS has poor performance because it tends to include wireless links between distant nodes, leading to more energy waste in retransmissions. On the contrary, EEOR and RMER select better paths by explicitly taking into account the quality of wireless links. Thanks to the advantage of OR, EEOR achieves the best performance. However, with the introduction of coordinated sleep scheduling, it is surprising that EEOR does not always consume the least amount of energy. EEOR w SS consumes more energy 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 transmission energy than any other routing protocol. Secondly, it requires more

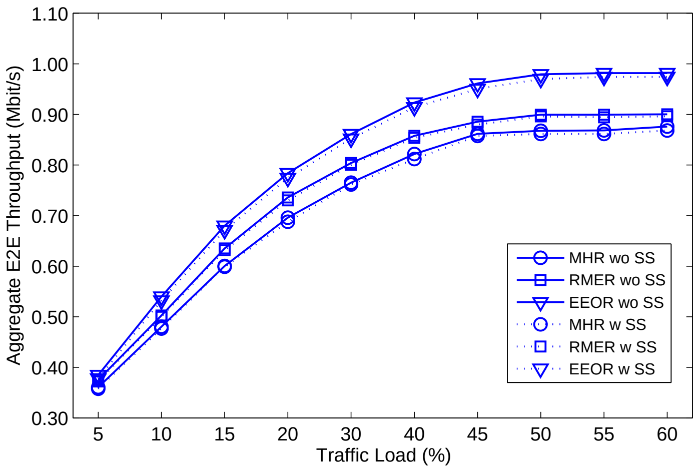

Fig. 5 Aggregate end-to-end throughput versus the traffic load

neighboring nodes to overhear the data packet, which consumes more energy in overhearing.

C. Aggregate end-to-end throughput

The results of aggregate end-to-end throughput are provided in Fig. 5. EEOR can achieve the best performances while MHR has the worst performance in terms of throughput. When the traffic load is increased to 50%, the network becomes congested and performances of the throughput of all routing protocols tend to be saturated. EEOR has higher throughput as a result of higher probability of successful transmission. Moreover, it makes use of multiple potential forwarders so that the total traffic load can be distributed more equally than other protocols. The function of coordinated sleep scheduling leads to some control packets overhead, but the performances loss is negligible, which results in the effectiveness of coordinated sleep scheduling.

D. Energy consumption per packet

Next, we examine the performance of network-wide energy efficiency. Fig. 6 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 monotonously decreases with the traffic load. The reason for the trend is that the energy wasted in idle listening is the dominant source of energy waste as compared with that for retransmissions, and the energy required for idle listening power is reduced as the traffic load increases. EEOR does achieve the highest energy efficiency, corresponding to the current conclusions drawn by existing works on OR protocols. In contrast, the performances of energy efficiency of different routing protocols with sleep scheduling show different results. From Fig. 7, it is not straightforward that EEOR does not always have the best performance. When the traffic load is relatively low, EEOR consumes more energy for each packet since the increased energy consumed by potential forwarders overwhelms the saved energy at transmitters in a good channel condition. Only under the condition that the packet loss occurs at a higher probability, EEOR can have a higher energy

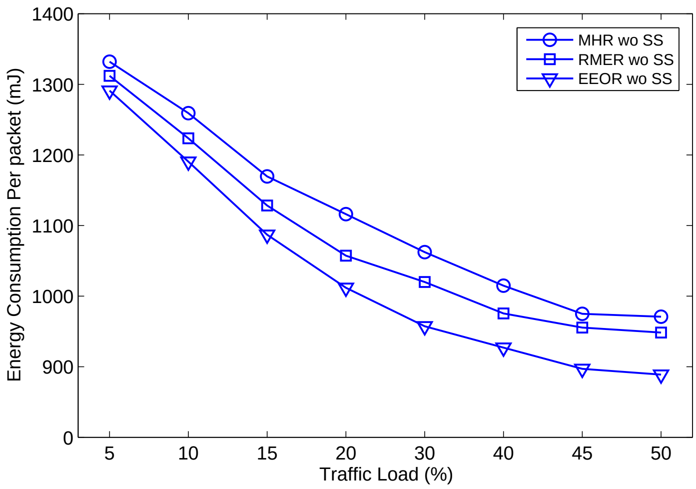

Fig. 6 Energy consumption per packet versus the traffic load under the use of routing protocols without sleep scheduling

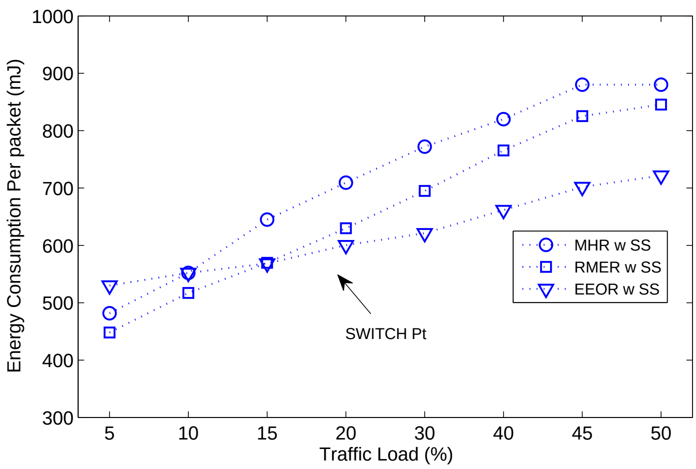

Fig. 7 Energy consumption per packet versus the traffic load under the use of routing protocols with sleep scheduling

efficiency. Otherwise, RMER saves the most energy per packet. This conclusion contradicts the existing study that OR protocols outperforms BPR protocols in terms of energy efficiency.

Overall, the impact of coordinated sleep scheduling on the routing protocols depends on the total traffic load over the network. EEOR protocol can achieve higher energy efficiency than RMER protocol only if the traffic load is relatively high when coordinated sleep scheduling is supported.

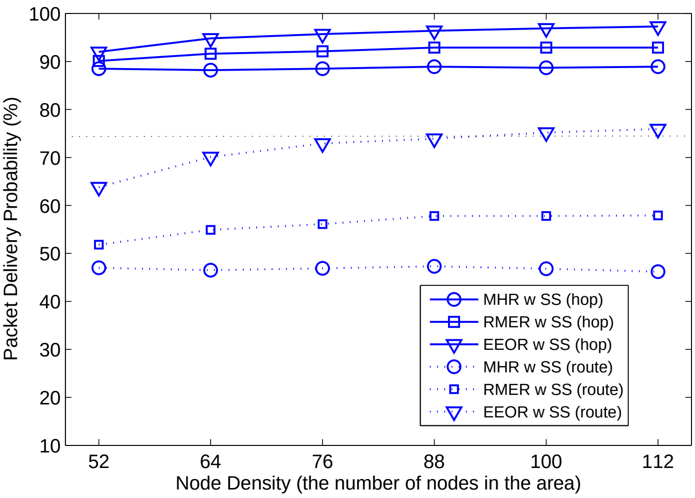

Fig. 8 Packet delivery probability versus the node density

5.3.2 Impact of node density

Network Scenario: The maximum transmit power P_T is 100 mW, and there are four macro cells in the whole area. The number of flows is always equal to the same proportion of 25% of the total number of nodes under different node densities. The traffic load T_l is 40% and remains the same. The total number of nodes N changes from the minimum 52 to the maximum 112 with a step size of 12 nodes.

A. Packet delivery probability

Fig. 8 shows the results of packet delivery probability with different routing protocols. Obviously, the performance 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 both sensitive to the node density. With an increase of node density, more links can be considered for route selection in the two routing protocols, so the packet delivery probability obtained by EEOR is hence increased [25].

B. Total energy consumption

Fig. 9 shows the total energy consumption of different schemes. For those routing protocols without sleep scheduling, the total energy consumed over the network increases with the number of total nodes due to increased overhearing energy waste. We reach the same conclusion as in [4] that more energy is wasted by overhearing when the node density is high. However, with the introduction of coordinated sleep scheduling, the amount of energy wasted in overhearing can be significantly reduced. The total energy consumption of all routing protocols with coordinated sleep scheduling hence decreases from that in Fig. 9. Similar to the results in Fig. 4, EEOR w SS consumes the most energy in comparison with the other two routing protocols w SS, which contradicts the conclusion derived from the results when sleep scheduling is not supported. We can further observe that

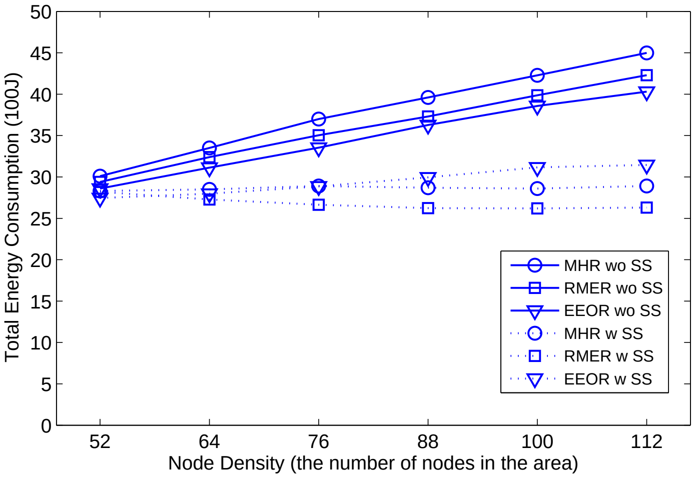

Fig. 9 Total energy consumption versus the node density

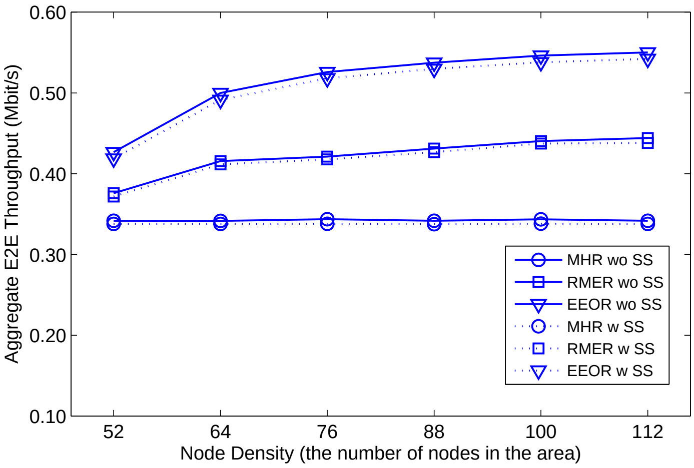

Fig. 10 Comparison of the aggregate end-to-end throughput versus the node density

total energy consumption of EEOR w SS slightly increases with the node density as a result of higher extra signalling power in the AC period.

C. Aggregate end-to-end throughput

The performance in terms of aggregate end-to-end throughput is shown in Fig. 10. Similar to the results of packet delivery probability, EEOR can achieve higher throughput than the other routing protocols, consistent with the conclusions drawn in literature. Overall, EEOR outperforms the other two routing protocols regardless of the function of coordinated sleep scheduling. The loss of performances with the introduction of sleep scheduling is negligible as compared with the improvement in throughput.

D. Energy consumption per packet

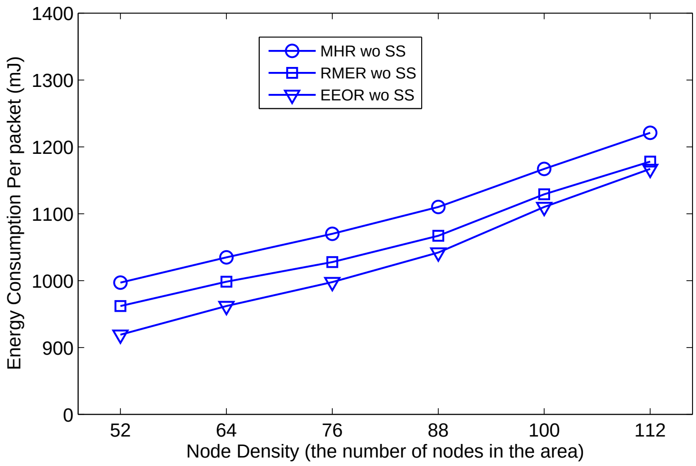

Fig. 11 Energy consumption per packet versus the node density under the use of routing protocols without sleep scheduling

From Fig. 11, we can observe that network-wide energy efficiency using different routing protocols without sleep scheduling decreases with the node density. The reason for that is more energy is wasted due to overhearing. Moreover, EEOR can achieve the highest energy efficiency in terms of energy consumption per packet among all the routing protocols, which demonstrates the benefit of multi-receiver gains. RMER outperforms MHR because it selects links with better quality. However, we notice that when the node density is relative high, e.g., 112, EEOR does not show obvious advantage over RMER. The reason for that is EEOR requires a number of neighboring nodes to receive the packet, which consumes more energy at those potential forwarders. The simulation results show that the benefit of energy efficiency achieved by EEOR does not proportionally increase with the node density. We compare the performance results of different routing protocols supporting coordinated sleep scheduling in Fig. 12. It is interesting to see that the energy efficiency obtained by EEOR no longer monotonously increases with the number of nodes in the network. There is an optimal point for the highest energy efficiency in terms of node density. When the node density consistently increases beyond this point, the benefit of energy saving achieved at transmitter nodes by EEOR cannot compensate for the increased energy consumption at forwarders. Consequently, EEOR can even obtain a lower energy efficiency than MHR until the limit of maximum candidate nodes is reached.

In summary, the impact of coordinated sleep scheduling depends on the network node density. There is an optimal node density for the highest energy efficiency in the EEOR protocol when coordinated sleep scheduling is supported. Moreover, EEOR can have a lower energy efficiency than RMER protocol when the node density is relatively high.

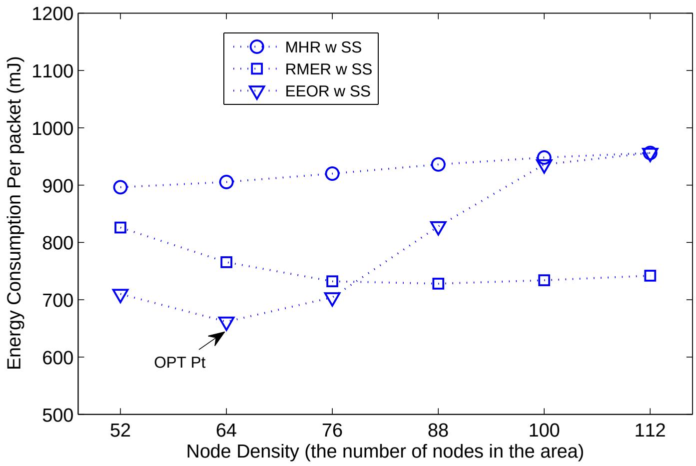

Fig. 12 Energy consumption per packet versus the node density under the use of routing protocols with sleep scheduling

6 Conclusions

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. We conduct a study of energy-efficient routing which supports coordinated sleep scheduling to increase network-wide energy efficiency. From our performance comparison, we reach a conclude that the OR protocol does not always outperforms the BPR protocol in terms of network-wide energy efficiency under different networking conditions. This observation challenges the existing conclusion on the advantage of OR protocols. We only consider a 2-D grid topology two network parameters in this work. In the future studies, we will consider more complicated network topologies and more network parameters to show the adaptability of the proposed work. Moreover, further studies are necessary to design the optimal energy-efficient routing protocols to maximize network-wide energy efficiency with consideration of the network parameters in wireless ad hoc networks.

References

1. Jones CE, Sivalingam KM, Agrawal P, Chen JC (2001) A survey of energy efficient network protocols for wireless networks. Wireless Networks 7(4):343-358
2. Stemm, M, Katz RH (1997) Measuring and reducing energy consumption of network interfaces in hand-held devices. IEICE Transactions on Communications 80(8):1125-1131
3. Ye W, Heidemann J, Estrin D (2004) Medium access control with coordinated adaptive sleeping for wireless sensor networks. IEEE/ACM Transactions on Networking 12(3):493-506
4. Singh S, Raghavendra, CS (1998) PAMAS-power aware multi-access protocol with signalling for ad hoc networks. ACM SIGCOMM Computer Communication Review 28(3):5-26
5. Tseng YC, Hsu CS, Hsieh YT (2003) Power-saving protocols for IEEE 802.11-based multi-hop ad hoc networks. Computer Networks 43(3):317-337

6. Guha S, Basu P, Chau CK, Gibbens R (2011) Green wave sleep scheduling: optimizing latency and throughput in duty cycling wireless networks. IEEE Journal on Selected Areas in Communications 29(8):1595-1604
7. Biswas S, Morris R (2005) ExOR: opportunistic multi-hop routing for wireless networks. ACM SIGCOMM Computer Communication Review 35(4):133-144
8. Vazifehdan J, Prasad RV, Niemegeers I (2013) Energy-efficient reliable routing considering residual energy in wireless ad hoc networks. IEEE Transactions on Mobile Computing 13(2):434-447
9. Kim J, Lin X, Shroff NB, Sinha P (2010) Minimizing delay and maximizing lifetime for wireless sensor networks with anycast. IEEE/ACM Transactions on Networking 18(2):515-528
10. IEEE Std. 802.11g (2003) IEEE standard for information technology - local and metropolitan area networks - part 11: wireless LAN medium access control (MAC) and physical layer (PHY) specifications: futher higher data rate extension in the 2.4 GHz Band
11. Du S, Saha AK, Johnson DB (2007) RMAC: A routing-enhanced duty-cycle MAC protocol for wireless sensor networks. Proceedings of IEEE International Conference on Computer Communications (INFOCOM), pp. 1478-1486
12. Scott K, Bambos N (1996) Routing and channel assignment for low power transmission in PCS. Proceedings of IEEE International Conference on Universal Personal Communications (ICUPC), pp. 498-502
13. Banerjee S, Misra A (2002) Minimum energy paths for reliable communication in multi-hop wireless networks. Proceedings of ACM International Symposium on Mobile Ad Hoc Networking & Computing, pp. 146-156
14. Zhong, Z., Nelakuditi, S.: On the efficacy of opportunistic routing. In: Proc. IEEE International Conference on Sensing, Communication, and Networkting (SECON) 2007, pp. 441-450
15. Dubois-Ferriè R, Henri, Grossglauser M, Vetterli M (2011) Valuable detours: Least-cost anypath routing. IEEE/ACM Transactions on Networking 19(2):333-346
16. Mao X, Tang S, Xu X, Li XY, Ma H (2011) Energy efficient opportunistic routing in wireless sensor networks. IEEE Transactions on Parallel and Distributed Systems 22(11):1934-1942
17. Gupta P, Kumar PR (2000) The capacity of wireless networks. IEEE Transactions on Information Theory 46(2):388-404
18. Liu Q, Zhou S, Giannakis GB (2004) Cross-layer combining of adaptive modulation and coding with truncated ARQ over wireless links. IEEE Transactions on Wireless Communications 3(5):1746-1755
19. Sutton GJ, Liu RP, Collings IB (2003) Modelling IEEE 802.11 DCF heterogeneous networks with rayleigh fading and capture. IEEE Transactions on Communications 61(8):3336-3348
20. Stü B, Gordon L (2011) Principles of mobile communication. Springer
21. Neely MJ, Urgaonkar R (2009) Optimal backpressure routing for wireless networks with multi-receiver diversity. Ad Hoc Networks 7(5):862-881
22. Draves R, Padhye J, Zill B (2004) Comparison of routing metrics for static multi-hop wireless networks. ACM SIGCOMM Computer Communication Review 34(4):133-144
23. Cisco (2012) Aironet Wireless LAN Adapters 350 series technical specifications, http://www.cisco.com
24. Zhang X, Liu Q, Shi D, Liu Y, Yu X (2007) An average link interference-aware routing protocol for mobile ad hoc networks. Proceedins of IEEE International Conference on Wireless and Mobile Communications (ICWMC), pp. 10-10
25. Luk CP, Lau WC, Yue OC (2008) An analysis of opportunistic routing in wireless mesh network. Proceedings of IEEE International Conference on Communications (ICC), pp. 2877-2883