Energy Efficient Reservation-based Opportunistic MAC Scheme in Multi-hop Networks

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Abstract—**Opportunistic forward techniques can improve the energy efficiency of wireless multi-hop networks by exploiting multiuser diversity. Opportunistic forward schemes generally integrate the functions of routing and MAC layers; nevertheless, most of the works focus on the design of routing protocol while assuming an energy efficient MAC layer. However, due to the unreliable links among the source node and its relay candidates, a great amount of energy expenditure results from the synchronization and multi-relay transmission, which degrades the energy performance of opportunistic forward techniques. In this paper, an energy efficient opportunistic MAC protocol with the mechanisms of reservation and a relay candidate coordination is proposed. Moreover, the multi-relay transmission probability is analyzed. Simulation and experiment results on a real wireless sensor network platform in different channels demonstrate the the proposed scheme greatly reduces the multi-relay transmission probability and achieves about 84% improvement of energy efficiency compared with the traditional opportunistic MAC schemes.**

I. Introduction

Energy efficiency is of great importance for the performance of wireless multi-hop networks because of the limit of power supply, cost, and size budget of wireless nodes. Although the advances in Radio Frequency (RF) circuits have been remarkable in recent years, a radio transceiver is still the most power-consuming component of a wireless node [1].

Opportunistic forward techniques are proposed to improve the energy efficiency of wireless networks by taking advantage of the use of spontaneous radio links [2]. In [3], the benefit of energy-delay performance from the opportunistic forwarding techniques is presented in different kinds of channels. The main principle of opportunistic forwarding is that, at each hop, there is a set of next-hop relay candidates in which some have successfully received a packet and compete for acting as a relay. During the relay selection phase, a priority is assigned to each relay candidate according to a predefined metric, for example, the geographical closeness of the relay candidate to the destination [4], as shown in Fig. 1.

The opportunistic forward schemes perform the functions of routing and MAC layers. The functions of routing layer include the selection of relay candidates and the assignment of priority, i.e, which node in the list of neighbors should be selected as relay candidate, how many relay candidates should be used and which principle is employed to assign the priority to each relay candidate. On the other side, the MAC layer is in charge of the synchronization between a source node and its relay candidates, the coordination of relay candidates and the collision-avoiding mechanism.

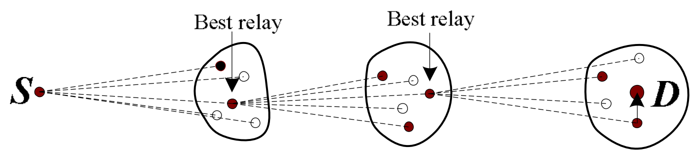

Fig. 1. Principle of opportunistic routings: dark nodes successfully received the data packet and one of them is chosen to relay information to the destination.

As for opportunistic routing protocols, lots of solutions are presented. According to the selection metric of relay candidate, they can be classified as [5]: geographical information based [6], [7], delivery-rate based [8], hop-count based [9], code-aware routing [10] and generic routing protocols [11]. The performance analysis of energy efficiency is also provided in these works. In [6], energy and latency performance of a routing scheme called *GeRaF* are analyzed, and the effects of node density, traffic load and duty cycle are evaluated. The simulations in [7] show the impacts of node density, radio channel quality and traffic rate on the energy consumption at each node, the average delay of packet and the goodput of opportunistic protocol. It is concluded that the benefit of opportunistic scheme is about 10% decrease in power and 40% reduction in delay. Furthermore, the energy efficiency of the geographical information-based *CAGIF* protocol [12] is studied in a fading channel. Therein, the whole set of neighbor nodes attempt to receive packets from the source node, which may degrade the energy performance. Accordingly, a selection mechanism of relay nodes is described in [4] in order to improve the energy efficiency. The corresponding simulation results in a shadowing channel indicate that the energy efficiency is greatly improved.

However, these analyses are grounded on the following two unrealistic aspects:

- $0-1$ link model: a wireless link is perfect when the received signal is stronger than a reception threshold level; otherwise, there is no link. Whereas, due to the complexity of wireless environment and possible movement of nodes or surrounding objects, a network in practice is an evolving process with unstable links and always remaining in an intermediate state, i.e., partially connected, as presented in [13] and [14].

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- Perfect opportunistic MAC layer: efficient synchronization between the source node and its relay candidates, efficient collision avoidance and multi-relay transmission avoidance are assumed. Nevertheless, the energy expenditure from the traditional synchronization process is considerable since its involved listening time may exceed that of data transmission and accordingly, the related power consumption of current radios is nearly at the same high level in the transmission and reception modes. In addition, due to the unreliable wireless links, there are quite a number of cases where the distance between two relay candidates is greater than that between the source node and relay candidates. In these cases, the coordination packet could not be successfully sent to all relay candidates in the relay coordination process. Thus, the same packet is transmitted to the destination more than one time, which leads to energy waste.

Consequently, regarding the important impact of MAC protocol on the energy efficiency, a reservation-based opportunistic (ROP) MAC scheme with three mechanisms is proposed in this paper. These three mechanisms consist of:

- Reservation mechanism: As mentioned above, the source node selects some of its neighbors as relay candidates instead of all neighbors. Normally, the number of relay candidates is smaller than 5. This provides a possibility to make a synchronization reservation between the source node and its relay candidates. Once a synchronization phase is performed between the source node and its relay candidates, the reservation is made among them for the following transmissions from this source node. That is to say, multiple transmissions from the same source node can profit from this synchronization, which contributes to energy reduction. Compared to this technique, in the traditional opportunistic MAC protocols, each transmission requires a new synchronization. Furthermore, the synchronization in the proposed reservation mechanism is realized by making a rendezvous among multiple nodes, i.e., the source and its relay candidates. Whereas for the classical reservation mechanism [15], the rendezvous merely involves two nodes, namely, a transmitter and a receiver.
- Relay candidate coordination mechanism: It makes use of channel correlation after a successful data transmission to broadcast the coordination packet so that this packet can be received by all relay candidates. Thus, the probability of multi-relay transmission is decreased to almost 0.
- Reservation based collision avoiding mechanism: The reservation table of each node is utilized to avoid the collisions of simultaneous transmissions from different source nodes.

With respect to the routing policy used in this paper, we assume that the relay candidate closest to the destination is selected to forward the packet. Such a strategy obviously relies on the assumption that each node has the full knowledge of the position of itself and the destination. If a node has a packet to send, it appends the locations of itself and the intended relay cluster to the packet, and then broadcasts it. The relay candidates which successfully receive the packet (solid nodes in Fig. 1) assess their own priorities of acting as relay, based on the information on how close they are to the destination. The *best relay* which is the closest to the destination forwards the packet, as shown in Fig. 1.

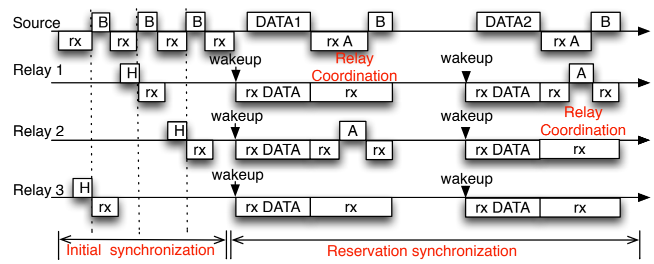


Fig. 2. Reservation-based opportunistic MAC protocol, where H, A and B denote *Hello*, *ACK* and *Beacon* packets, respectively.

The remaining part of this paper is organized as follows: In Section II, the proposed reservation-based opportunistic MAC protocol is presented. Moreover, the corresponding probability of multi-relay transmission is analyzed. Section III-A describes the employed system energy and link models. Then, the energy efficiency of the proposed protocol is shown by simulations and experiments in Section IV. Finally, Section V gives some conclusions.

II. Description of ROP MAC

The proposed ROP MAC protocol is presented in this section, as illustrated in Fig. 2. In the considered network, each node preserves two synchronization tables for transmitting and receiving respectively. In the transmitting synchronization table, the destination ID and its corresponding synchronization time are recorded. Similarly, the source ID and its corresponding synchronization time are saved in the receiving synchronization table. When a node has a packet to transmit, it will check if the destination ID of this packet is in its transmitting synchronization table. If yes, the packet will be transmitted at the reserved time; otherwise, an initial synchronization is launched in order to synchronize its relay candidate. After this initial synchronization phase, the source and its relay candidates make a rendezvous to implement the current data transmission. When the data transmission is finished, a relay candidate coordination ensures that only one relay candidate forwards this packet. During the coordination process, the rendezvous for the following transmission is informed to each relay candidate. Subsequently, the data transmission and relay candidate coordination processes for the following packet can be repeated in this way until some constraint is met, for example, the maximum number of repetitions or the change of relay candidates. In the following, ROP MAC is described in detail from its three parts: synchronization, collision avoidance and relay candidate coordination.

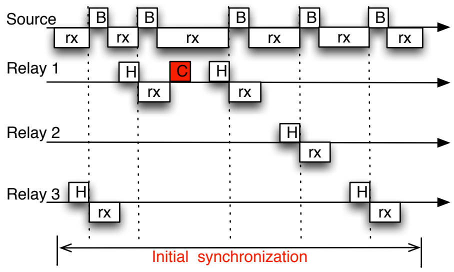


Fig. 3. Collision avoiding mechanism, where H, B and C denote *Hello*, *Beacon* and *Collision* packets, respectively.

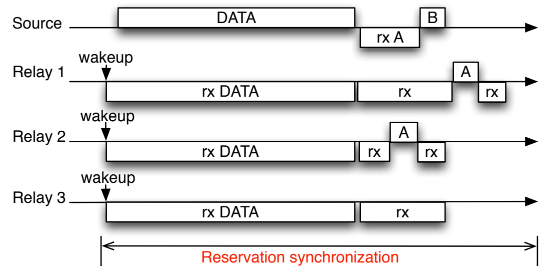


Fig. 4. Relay candidate coordination mechanism, where A and B denote *ACK* and *Beacon* packets, respectively.

A. Synchronization Process and Collision Avoiding Mechanism

The synchronization process includes two phases: initial synchronization and reservation synchronization, as shown in Fig. 2. During the initial synchronization phase, the source node firstly calculate the synchronization time according to its synchronization table. Then, it waits for the *Hello* packets from its neighbors. When the source node receives a *Hello* packet from one node whose ID is in the list of the source's relay candidates, it will send a *Beacon* packet immediately to this node, in which the information about the related synchronization time and priority is included. If the relay candidate (for example, Relay 1) receives the *Beacon* packet from the source, it will firstly search if the rendezvous encounters collisions with the other nodes in its receiving and transmitting synchronization tables. If there is no collision, Relay 1 will record the source ID and corresponding synchronization time in its receiving synchronization table. On the contrary, in the case of initial synchronization collisions, Relay 1 sends a collision packet to the source node to relaunch this initial synchronization process, as shown in Fig. 3. When the source node receives the *Collision* packet, it will add the double duration of data transmission time to the synchronization time so as to avoid the current collision, and subsequently restart the synchronization process. The reservation synchronization phase is described in Section II-B.

B. Relay Candidate Coordination Mechanism

After the data transmission, the relay candidates that receive the data packet will compete for acting as relay to forward the data based on their backoff time. The backoff time of each relay candidate depends on its priority, and a higher priority implies a shorter backoff time. As described in Section I, the multiple relays are mostly caused by the fact that the links among relay candidates are terrible due to the big transmission distance. In the proposed mechanism of relay coordination, two different transmission paths are employed to achieve the coordination in order to avoid the collisions of multiple relays: the first one is the path from relay node to relay candidates, and the second one is the path from source to relay candidates.

During the coordination procedure, the relay candidates begin their own backoff processes simultaneously and wait for the acknowledgement (*ACK*) packet, as described in Fig. 2. When a relay candidate finishes its backoff period and does not detect any *ACK* packet (for example, Relay 2), it will send an *ACK* packet to the source node and the other relay candidates. After receiving the *ACK* packet, the source node will reply to the relay node and the other candidates with a *Beacon* packet immediately. In such a way, the other relay candidates will drop the received data packet after receiving the *ACK* and/or *Beacon* packet. While the relay node receives the *Beacon* packet, it will save the received data packet in the buffer and prepare to forward it. Additionally, the *Beacon* packet includes the reservation synchronization time and this time is recorded in the corresponding receiving synchronization table at the relay candidates.

It should be noted that the advantage of this coordination mechanism is that two packets by different transmission paths are used to avoid the collisions of multiple relay nodes: *ACK* and *Beacon* packets. The *ACK* packet is transmitted from the relay node to the other relay candidates, and the *Beacon* packet is from the source node to all relay candidates. By exploiting this kind of diversity, the probability of multi-relay can be greatly reduced. In addition, the link probability between the relay and the source is generally higher thanks to the channel correlation [16]. The probability of multiple relays is analyzed in Section III-B.

Fig. 4 illustrates the proposed coordination mechanism with an example. In this example, Relay 2 firstly finishes its backoff process and sends an *ACK* packet to its neighbors. Among these neighbors, all nodes except Relay 1 (for example, due to a big distance) receive this *ACK*. Subsequently, Relay 3 will drop its received packet and wait for the *Beacon* packet from the source. After the *Beacon* is sent, the coordination process is completed. For Relay 1, if it does not receive the *Beacon* packet after detecting the failure of *ACK*, it will send its own *ACK* to the source. In this case, this transmission of *ACK* does not induce Relay 1 to forward its received data packet since only the relay candidate that receives the *Beacon* can forward the data. Finally, Relay 1 will fall out of the competition of acting as relay node.

TABLE I
NOTATIONS

Symbol	Description	Value
α	Path-loss exponent (≥ 2)	3
β_{amp}	Amplifier proportional offset (> 1)	14.0
γ	Signal-to-noise ratio	
b	Number of bits per symbol	$\log_2(M)$
B	Channel bandwidth	250 KHz
f_c	Carrier frequency	2.4 GHz
G_{Rant}	Receiver antenna gain	1
G_{Tant}	Transmitter antenna gain	1
L	Circuitry loss	1
M	Modulation order	
N_0	Noise level	$-150\, dBm/Hz$
N_{ack}	Number of bits in an *ACK* packet	78
N_b	Number of bits per packet	1600
N_{head}	Number of bits in the overhead of a data packet	0
P_{rxElec}	Receiver circuitry power	59.1 mW
P_{start}	Startup power	38.7 mW
P_t	Transmission power	
P_{txElec}	Transmitter circuitry power	59.1 mW
R_b	Bit rate	250 $kbps$
R_{code}	Code rate	1
R_s	Symbol rate	
T_{start}	Startup time	0 μs

III. ANALYSIS OF PROPOSED PROTOCOL

A. System, Energy and Link Models

This section introduces the problem formulation by modeling the considered system, energy consumption and wireless links. For the readability, all parameters used in this paper are described in Table I. The values about node parameters are obtained from the PowWow platform [17].

1) System Model: In this paper, the nodes in a network are assumed to be independently and randomly distributed according to a random Poisson process with density ρ. The probability of finding n nodes in a region $\mathcal{A}$ follows a two-dimensional Poisson distribution:

$$P(n\, nodes\, in\, \mathcal{A}) = \frac{(\rho \cdot S_A)^n}{n!} \exp(-\rho \cdot S_A), \quad (1)$$

with $E[n] = \rho \cdot S_A$. Here, S_A is the surface of $\mathcal{A}$ and $\exp(\cdot)$ represents the exponential function.

We consider the case of a source node $\mathcal{S}$ forwarding a packet to a sink/destination node $\mathcal{D}$. n_i is one of $\mathcal{S}$'s neighbors which is closer to $\mathcal{D}$ than $\mathcal{S}$. We assume that $\mathcal{S}$ is aware of its own location and those of its neighbors and the destination $\mathcal{D}$. $\mathcal{S}$ obtains the link probabilitie pl of each neighbor using (4) so that it can select a set of forwarding candidates among its neighbors according to some predefined measurement, e.g., the distance to the destination node.

2) Energy Consumption Models: In this work, these energy consumption components are expressed on the basis of the models in [3]: for the transmission,

$$E_{Tx} = T_{start} \cdot P_{start} + \frac{N_b + N_{head}}{R_b \cdot R_{code}} \cdot (P_{txElec} + \beta_{amp} \cdot P_t), \quad (2)$$

and for the receiving process,

$$E_{Rx} = T_{start} \cdot P_{start} + \frac{N_b + N_{head}}{R_b \cdot R_{code}} \cdot P_{rxElec}. \quad (3)$$

Please refer to Table I for the definitions of all related parameters in (2) and (3).

3) Realistic Unreliable Link Models: As described in Section I, transmission errors play an important role in the reliable communications. Hence, we consider herein the radio link probability $pl(\gamma)$ as the metric of link quality, which is derived from the packet error rate (PER) [3] as

$$pl(\gamma) = 1 - PER(\gamma), \quad (4)$$

where $PER(\gamma)$ is the PER obtained according to a signal-to-noise ratio (SNR) γ at the receiver. γ is obtained from the classical attenuation model in [18]:

$$\gamma = K_2 \cdot P_t \cdot d^{-\alpha}, \text{ with } K_2 = \frac{G_{Tant} \cdot G_{Rant} \cdot \lambda^2}{(4\pi)^2 N_0 \cdot B \cdot L}, \quad (5)$$

where d denotes the transmission distance between two nodes, and B is equal to R_s for the sake of simplicity. Refer to Table I for the other parameters. The approximations of this unreliable link model for the additive white Gaussian noise (AWGN) and Rayleigh block fading channels are presented in [3].

B. Analysis of Multi-relay Transmission Probability

According to the description of relay candidate coordination mechanism, for each hop, the multiple transmission may happen in the case when the source node does not receive the *ACK* packet or when the relay node does not receive the *Beacon* packet. Thus, we have

$$p_{mtp} < (1 - pl_{ack}) + pl_{ack}(1 - pl_{beacon}) = 1 - pl_{ack}pl_{beacon}, \quad (6)$$

where p_{mtp} is the probability of multiple transmissions of one hop, pl_{ack} and pl_{beacon} are the successful transmission probability of *ACK* and *Beacon* respectively. pl_{ack} and pl_{beacon} are calculated by (4).

Actually, $pl_{ack} \approx 1$ and $pl_{beacon} \approx 1$, due to the following three aspects: Firstly, the size of *ACK* packets is supposed to be much smaller than that of data packets. For instance, when the size of *ACK* and data packets are 10 and 200 bytes respectively, the successful transmission probability is 80% for data packets, whereas 98% for *ACK* packets. Secondly, we assume that the data, *ACK* and *Beacon* packets experience the same channel state owing to the channel correlation in a short time ($\leqslant 20ms$) [16]. Hence, pl_{ack} and pl_{beacon} can be approximated to 1 under the condition of a successful data transmission. Thirdly, a more efficient coding scheme can be used to improve the reliability of transmissions if necessary. Under the aforementioned assumptions, we obtain

$$p_{mtp} \approx 0. \quad (7)$$

Furthermore, the experiment results about multi-relay transmission probability are demonstrated in Section IV, which are consistent with this analysis.

IV. Simulations and Experiments

The performance of ROP MAC is evaluated through simulations and experiments in this section. The simulation and experiment results are compared in terms of the energy consumption per packet for the proposed scheme. Besides, we present the energy-delay performance of the proposed scheme, the traditional opportunistic MAC and the theoretical lower-bound from [3].

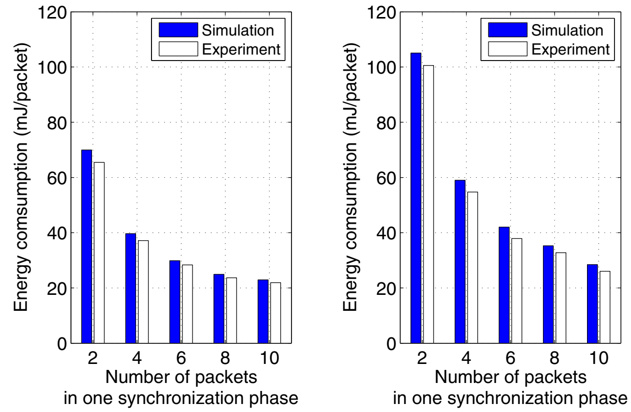
In the simulations and experiments, the closeness policy [3] is adopted at the routing layer, i.e., the closest relay candidate to the destination is selected as the relay node. The MAC protocol proposed in Section II is employed at the MAC layer. With respect to the link layer, the transmitter of each hop will repeat the transmission process until the data packet reaches the following relay node. That is to say, there is no constraint of retransmission number. In all scenarios, the source node generates a *Data* packet of 200 bytes every one second. The *ACK* and *Beacon* packets are of 10 and 15 bytes respectively.

A. Simulation and Experiment Setup

1) Simulation setup: The WSNet simulator [19] is used. 50 wireless nodes are deployed in an area $\mathcal{A}$ with surface $S_{\mathcal{A}} = 100 \times 400m^2$. The nodes are uniquely deployed according to the Poisson distribution. The distance between the source and destination is 400m. In the simulations, the transmission power of each node is set as the same value (0dBm). All other parameters concerning a node are listed in Table I. Each kind of simulation is executed in two types of channels: the AWGN and Rayleigh block fading channels corresponding to the outdoor and indoor environments. Every scenario is repeated for 1000 independent simulation runs in order to obtain an average value.

2) Experiment setup: All experiments in this paper are implemented on the PowWow platform [17]. The wireless nodes of this platform are composed of a motherboard, embedded an MSP430 microcontroller and the other needed components, as well as a radio-chip daughter board based on a CC2420. In terms of the AWGN channel, 10 nodes are deployed in an outdoor environment: the garden park outside the office. On the other side, the Rayleigh block fading channel is implemented in an indoor environment, i.e, the corridor of office. The 10 nodes are organized into four groups: one source node as one group and every three nodes for each one of the remaining three groups. The distance of each group is similar and is set as the optimal transmission distance obtained according to the theoretical results in [3]. The distance between two nodes in the same group is about 3 to 4 meters.

In the experiments, the transmission power of each node is set as 0dBm which is the maximum value of the utilized radio chip. The transmission rate is 250kbps, and the modulation is orthogonal-quadrature phase-shift keying (O-QPSK) [20]. All parameters in the MAC and routing layers are the same as those in the simulations.



(a) AWGN channel (b) Rayleigh block fading channel

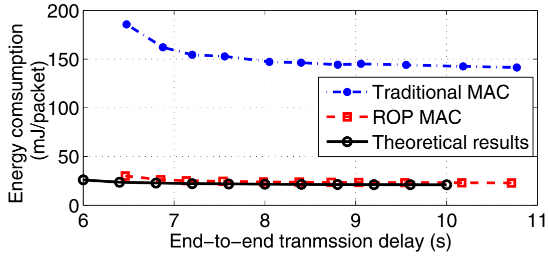
Fig. 5. Effect of the number of *Data* packets in one synchronization phase in two different channels.

B. Results and Analysis

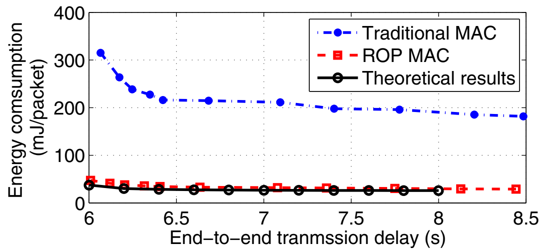
1) Impact of the Data packet number on energy consumption in one synchronization phase: In Fig. 5, the impacts of the number *Data* packet number in one synchronization phase on the energy consumption per packet are presented for the AWGN and Rayleigh block fading channels respectively. When one node transmits/forwards 2, 4, 6, 8 or 10 data packets each time, it restarts the initial synchronization process as described in Section II-A. Because the initial synchronization process takes a great amount of total energy expenditure, more *Data* packets sharing one synchronization process can bring a lower energy consumption per packet. Obviously, the energy consumption per packet of the transmission of 10 packets each time is dramatically lower than that of 2 packets per transmission. Additionally, the energy performance of experiments is slightly higher than that of simulations since the distance between nodes is optimized according to the formula (43) in [3].

2) Energy-delay tradeoff: Fig. 6 shows the energy-delay performance of the proposed scheme, traditional opportunistic MAC and theoretical results in [3] for the AWGN and Rayleigh block fading channels respectively. The theoretical results are actually the lower-bound of energy-delay which is obtained by neglecting the energy consumption from the synchronization [3]. With respect to the traditional opportunistic MAC protocol, the synchronization process is executed for each data transmission. In the simulations, 10 and 1 data packets are transmitted in one synchronization phase for the proposed scheme and traditional opportunistic protocol, respectively. The related transmission power is set as the optimal value obtained from [3].

The results in Fig. 6 demonstrate that the energy consumption of synchronization process represents a considerable portion of the total energy consumption in traditional MAC schemes. Whereas, the proposed reservation-based MAC scheme makes this part of energy expenditure undertaken by multiple transmissions, which contributes to reducing about



(a) AWGN channel



(b) Rayleigh fading channel

Fig. 6. Comparison of energy-delay tradeoff in different channels.

84% of energy consumption in both types of channels.

3) Probability of multi-relay transmission: Thanks to the proposed relay candidate coordination mechanism, multi-relay transmissions are not observed in the experiments because the distance between any two nodes is greatly smaller than that between the source node and its relay candidates. On the other side, in the simulations, multi-relay transmissions happen with a very low probability ($< 0.4\%$) for 10 groups of simulations in the AWGN and Rayleigh block fading channels. These results confirm the related analysis in Section III-B and indicate that the proposed coordination mechanism can effectively avoid the multi-relay transmissions.

V. Conclusions

The ROP MAC scheme which improves the energy efficiency of wireless multi-hop networks is presented in this paper. By exploiting the reservation mechanism, multiple packet transmissions in one synchronization phase share the energy consumption of the initial synchronization process. Meanwhile, a mechanism of relay candidate coordination is proposed to reduce the energy waste caused by multiple transmissions of the same data packet. In addition, the utilization of reservation tables further avoids the transmission collisions from different relay candidates. The theoretical analysis of the probability of multi-relay transmissions is provided. Finally, simulation and experiment results in different channels demonstrate that the proposed scheme highly reduces the multi-relay transmission probability and achieves about 84% improvement of energy performance compared with the traditional opportunistic MAC schemes. The ROP MAC can be integrated with any opportunistic routing protocol, especially for static networks or slowly mobile networks.

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