A Joint Design of Opportunistic Forwarding and Energy-Efficient MAC Protocol in Wireless Sensor Networks

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***Abstract*— Motivated by the highly dynamic topology in wireless sensor networks with asynchronous duty cycle, and its impact on reliable data delivery, we propose a light-weight opportunistic forwarding (LWOF) scheme. Differing from other recently proposed schemes, LWOF neither employs historical network information nor a contention process to select a forwarder prior to data transmission. It takes advantage of the preamble in low power listening (LPL) media access control (MAC) protocols and dual-channel communication to remove the overhead of making a forwarding decision. Along with LWOF, we propose an energy-efficient MAC protocol (LWMAC) with a shortened preamble, to exploit the non-deterministic characteristics of opportunistic forwarding. The preamble length in LWMAC is a function of the node density and sleep duration. Simulation results show that LWOF, along with LWMAC, can provide reliable service of data delivery with less energy consumption.**

I. INTRODUCTION

Sensor networks are often deployed to monitor the physical environment, and information sensed by the nodes are expected to be *reliably* forwarded to a sink in an ad-hoc way. However, lossy links pose major challenges to reliable data delivery [1]. Furthermore, the asynchronous duty cycle [2], [3] makes it even more difficult to reliably deliver a packet to the sink.

Considering the lossy links and highly dynamic topology in duty-cycled or mobile sensor networks, some protocols based on opportunistic forwarding have been proposed for reliable data delivery. In opportunistic forwarding, the node that forwards a packet is determined on-the-fly. Two recently proposed opportunistic forwarding schemes are OF (Opportunistic Forwarding) [4] and ROF (Receiver-based Opportunistic Forwarding) [5]. These two protocols differ in how the forwarder is determined. The former uses local network information to make a forwarding decision at the transmitter side, while the latter uses a contention process to make this decision at the receiver side.

Since overhead is incurred to maintain local network information or to conduct a contention, we propose a *light-weight* opportunistic forwarding scheme without determining the best forwarder prior to data transmission. Our scheme takes advantage of the preamble in a low power listening (LPL) MAC protocol (e.g., B-MAC [3]), which is widely used in wireless sensor networks with *asynchronous* duty cycle, to forward a packet to a unique downstream node towards the sink. At the same time, the MAC protocol exploits the non-deterministic characteristic of opportunistic forwarding to reduce the preamble length for energy efficiency. *So the scheme proposed in this paper is a joint design of opportunistic forwarding and energy-efficient MAC protocol in wireless sensor networks with asynchronous duty cycle*. The main contributions of the paper are as follows.

1) A light-weight opportunistic forwarding scheme (LWOF) is proposed to provide reliable data delivery for wireless sensor networks with asynchronous duty cycle. It can successfully forward a packet to a unique downstream node towards the sink with a high probability, without making a forwarding decision at each hop.
2) Exploiting the non-deterministic characteristic of opportunistic forwarding, an energy-efficient MAC protocol with reduced preamble length, named LWMAC, is jointly proposed.
3) Performance of the proposed protocol is evaluated through extensive simulations, in terms of packet delivery ratio, latency, and normalized energy consumption (Joules per packet).

The rest of the paper is organized as follows. Section II gives an overview of the related work. Section III describes the joint design of opportunistic forwarding and energy-efficient MAC protocol. Relationship among the preamble length, node density and node sleep duration is derived. Section IV evaluates our proposed schemes via simulations, and Section V concludes and identifies the future work.

II. RELATED WORK

Some opportunistic forwarding schemes have been proposed to mitigate the impacts of lossy link and dynamic topology on reliable data delivery. These protocols can be divided into two categories.

1) **Sender-based Opportunistic Forwarding:** Based on the historical network information (e.g., positions, duty cycles, and connectivity probabilities of the neighbor nodes) or instantly probed information, the sender selects one node as the forwarder of the packet prior to

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data transmission. GPSR (Greedy Perimeter Stateless Routing) [6], SDF (Selective Diversity Forwarding) [7], MAC-layer anycasting [8] and OF (Opportunistic Forwaring) [4] are examples of such kind of forwarding protocols.

2) **Receiver-based Opportunistic Forwarding:** In such schemes, it is the receiver, rather than the sender, who is responsible for determining the forwarder of the packet. Most of the currently proposed protocols are of this kind, including GeRaF (Geographic Random Forwarding) [9], CBF (Contention Based Forwarding) [10], IGF (Implicit Geographic Forwarding) [11], PFR (Probabilistic Forwarding) [12], ROF (Receiver-based Opportunistic Forwaring) [5] and C-MAC [13]. They employ a timer-based contention process to make the forwarding decision. In particular, when a node has a packet to be forwarded to the next hop, it will broadcast a message (e.g., Request To Send (RTS)) to announce the forwarding demand. Each active neighbor node will determine the backoff time to reply to the demand, based on its own local information such as geographical position and available energy. The one with the shortest backoff will be chosen as the forwarding node. For ExOR [14], the receiver makes the forwarding decision based on prior knowledge of the network topology.

The general idea of the light-weight opportunistic forwarding protocol (LWOF) proposed in this paper is essentially different from all the above schemes, in that it neither uses historical network information nor a contention process to select a forwarder prior to data transmissions. Taking advantage of the preamble in the LPL MAC protocol, which are widely used in the wireless sensor networks with *asynchronous* duty cycle, LWOF removes the overhead of making a forwarding decision prior to data transmissions.

To reduce the cost induced by the preamble in the LPL MAC protocol, some schemes such as the strobed preamble in X-MAC [15], adaptive polling in SCP [16] and RI-MAC [17], have been proposed to reduce the preamble length. The scheme in LWMAC is essentially different from these protocols, in that it exploits the non-deterministic characteristic of opportunistic forwarding to reduce the preamble length.

III. FORWARDING SCHEME DESIGN

In this section, we introduce the joint design of opportunistic forwarding and energy-efficient MAC protocol.

A. System model and assumption

Sensor nodes are uniformly deployed in an area of A square meters, with one sink to collect data. To save power, nodes alternates between active and sleeping states independently. In other words, each node works on its own duty cycle schedule. An LPL MAC protocol, such as B-MAC [3], is adopted to address the networking problem induced by the asynchronous duty cycle. As shown in Figure 1, prior to data transmission, a sender transmits a preamble lasting at least as long as the sleep period of the receiver. When the receiver wakes up and detects the preamble, it stays awake to receive the data. In this way, no matter when the destined neighbor wakes up, it can detect the arrival of the packet.

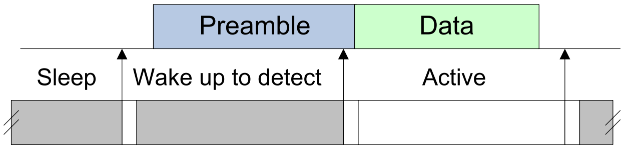

Fig. 1. Packet transmission with an LPL MAC protocol (B-MAC)

Each node obtains its location (x, y) through Global Positioning System (GPS) or self-configuring localization mechanisms [18]. The location of the sink is broadcasted to all sensor nodes during network initialization. Packets are forwarded to the sink using the location-address semantic [6], in which locations, instead of node IDs, are specified as the routing destinations. This location-address semantic is valid in many sensor networks, because sensor data, such as temperature readings, are normally tagged with the location information.

Sensor nodes support dual channel [19]. One is a low data rate channel for transmitting busy tone message, while the other is a higher data rate channel for transmitting sensor data. The former is referred to as the signal channel, while the latter is referred to as the data channel in the following sections.

B. LWOF design

As described in the above subsection, when employing an LPL MAC protocol, all the neighbor nodes waking up asynchronously can detect the preamble and receive the packet. However, the preamble cannot be detected by all the neighbor nodes at the same time. The novelty of LWOF is that it takes advantage of the sequential detection of preamble and busy tone signalling to reliably forward a packet to a unique downstream node on-the-fly, without making a forwarding decision based on the local network information or a contention process.

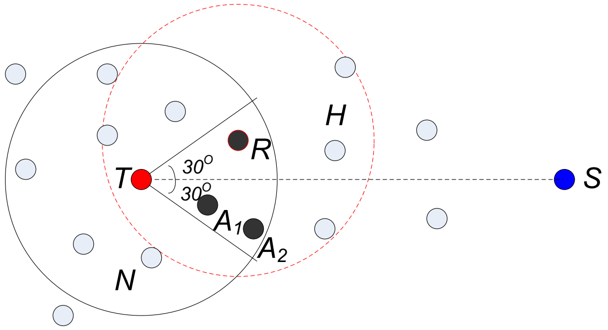

Fig. 2. Illustration of a scenario where a node T is transmitting a packet towards the sink S

We introduce our LWOF design with a simple example. Figure 2 depicts a scenario where a node T is transmitting a packet towards the sink S. As in [11], we define the dark nodes A_i as forwarding candidates, which are within a 30-degree radian area around the line connecting the sender

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and the sink on both sides. Within this 60-degree sector, the distance between any two nodes is smaller than the nominal communication range, so they can overhear each other and no hidden forwarder exists in the area. Outside of this 60-degree sector, the gray nodes N within the communication range of T are deprived of forwarding rights. When node T initiates a packet transmission, the following steps are taken to forward the packet to a unique downstream node towards the sink:

1) **Packet transmission:** When node T senses the signal channel idle, it starts transmitting the packet with a preamble in the data channel. The preamble contains the sender's and the sink's locations, instead of the meaningless hex number (e.g., 0xAA or 0x55) in the traditional LPL MAC protocol.
2) **Preamble detection and packet reception:** Nodes in the communication range of the sender T, and who wake up and detect the preamble of the packet, do the following computation to determine whether they are located in the 60-degree sector, using the the sender's location and the sink's location included in the preamble, and its own location.

   $$Degree_{\angle NTS} = acos\left(\frac{|TN|^2 + |TS|^2 - |NS|^2}{2|TN||TS|}\right)$$

   $|TN|$, $|TS|$ and $|NS|$ represent the Euclidean distances among the sender T, the sink S, and the receiver N. If the angle $\angle NTS$ is larger than 30 degrees, the receiver will turn off its data radio. Otherwise, it will send a busy tone in the signal channel immediately, and occupy the signal channel until the packet is received. The busy tone indicates the data channel is busy and prevents the hidden terminals from sending packets simultaneously. Besides, it also serves as a signal indicating that the packet has been received by one of the nodes in the 60-degree sector. Others sensing the busy tone will keep sleeping until the next scheduled waking up. So the function of the busy tone are two-fold. One is to solve the hidden terminal problem as in PAMAS [20], and the other is to prevent duplicate forwarding. As shown in Figure 2, node R in the 60-degree sector wakes up and detects the preamble. So it sends a busy tone in the signal channel, and nodes A_i sensing the busy tone will keep on sleeping. The hidden terminal H will defer sending until it senses the signal channel idle. It is worth noting that the duplicate forwarding problem is resolved based on the following inference.

   INFERENCE: In a wireless sensor network with asynchronous duty cycle, the probability that more than one node wake up simultaneously is almost zero.

   We will give a brief proof of the above inference in the following subsection.
3) **No acknowledgement:** We consider that sensor nodes are deployed with high density, and the void problem (i.e., the absence of nodes in the forwarding area) [6] can be neglected. Besides, we assume that the receiver R detecting the preamble has a high probability of receiving the packet successfully. So we eliminate the acknowledgement to reduce the cost of packet transmission in each hop.

C. LWMAC design

We note that the LPL MAC protocol is originally designed for unicast in wireless sensor networks with asynchronous duty cycle. In other words, packets are forwarded to a specific node at each hop, but the transmitter does not know when the forwarding node will wake up. So it must employ a sufficiently long preamble to ensure the packet is detected by the next hop. When the data rate is constant, the preamble length increases linearly with the sleep duration, i.e., the original preamble length measured in bits is $(T_s \cdot R_d)$, where T_s is the sleep duration and R_d is the data rate.

We exploit the non-deterministic characteristic of opportunistic forwarding to propose a new LPL MAC protocol, named LWMAC, which employs a much shorter preamble. As shown in Figure 3, the packet is transmitted with a preamble of length shorter than $(T_s \cdot R_d)$. One node in the forwarding area may not detect the preamble when it wakes up, but another node waking up τ time units later may detect it. For LWOF, any node who first detects the preamble can be the forwarder of the packet, so the packet with a shorter preamble can still be forwarded. Now the question is *how long a preamble is suitable for opportunistic forwarding*.

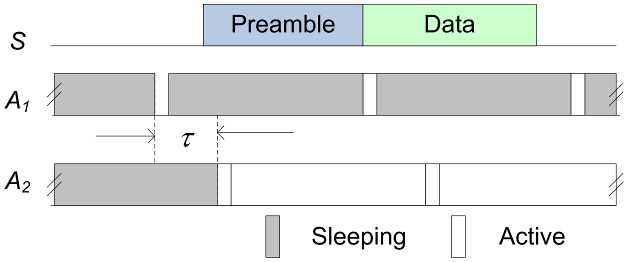

Fig. 3. Packet transmission with LWMAC protocol

Now we analyze the relationships among the preamble length, node density, and sleep duration. As shown in Figure 2, N_f nodes in the forwarding area wake up asynchronously after sleeping for T_s. We assume that the phase difference between two asynchronously duty-cycled nodes is a exponentially distributed random variable with average T_s/N_f. So we can view the sequence of nodes' waking up as a Poisson process, and the probability P_t that more than one node wake up in a period t can be formulated as follows.

$$\begin{aligned} P_t &= 1 - e^{-\frac{N_f}{T_s}\cdot t} - \frac{N_f}{T_s}\cdot t \cdot e^{-\frac{N_f}{T_s}\cdot t} \\ &= 1 - (1 + \frac{N_f}{T_s}\cdot t)\cdot e^{-\frac{N_f}{T_s}\cdot t} \end{aligned} \tag{1}$$

From the above equation, we can see that when the period t is extremely short (approaching zero), P_t approaches zero. This proves the inference in the previous subsection.

For the same reason, we can get the forwarding probability P_f that at least one node wakes up in a period T_p, where T_p is the length of the preamble.

$$P_f = 1 - e^{-N_f \cdot T_p / T_s} \tag{2}$$

For LWOF, the forwarding area is a 60-degree sector (see its definition in Section III-B), so the number of nodes in the forwarding area N_f in Equation (2) can be formulated as follows.

$$N_f = \frac{\pi r^2}{6} \cdot D, \tag{3}$$

where D is the node density, and r is the nominal radio range. From Equations (2) and (3), we can formulate the length of the preamble as a function of node density and sleep duration, as shown in Equation (4).

$$T_p = \min\left[-\ln(1 - P_f) \cdot \frac{6 \cdot T_s}{\pi r^2 \cdot D},\ Ts\right] \tag{4}$$

Figure 4 illustrates the relationship between the preamble length and the node density for LWMAC with different forwarding probabilities. Here we fix the sleep duration T_s to 135 ms and the radio range r at 20 meters. We can see that LWMAC takes advantage of the increase in node density to shorten its preamble. In other words, as more nodes are deployed in the field, the preamble length can be reduced while guaranteeing the same forwarding probability.

Figure 5 illustrates the relationship between the preamble length and the sleep duration for LWMAC with different forwarding probabilities, when the node density is fixed to 0.03 and the radio range r is 20 meters. We can see that like the LPL MAC protocol the preamble length of LWMAC is linearly proportional to the sleep duration, but it is much smaller than that of the LPL MAC protocol.

IV. PERFORMANCE EVALUATION

To assess the performance, we implement the light-weight opportunistic forwarding (LWOF) protocol, along with the energy-efficient MAC (LWMAC) protocol in network simulator (ns-2). For comparison, the LPL MAC (B-MAC) protocol is implemented as a special case of the LWMAC protocol, which employs a preamble of fixed length equal to the sleep duration. In addition, the opportunistic forwarding (OF) scheme [4] is implemented for the purpose of comparison. As described in Section II, OF is a sender-based opportunistic forwarding scheme, which uses the network information about the neighbors' duty cycle to make a forwarding decision. The network information is maintained by a priori exchange of a set of parameters of duty cycling. The simulation scenario is described below.

We put 300 nodes uniformly in a square region of 100 meters by 100 meters. Each node turns its own data radio on and off independently. In particular, nodes keep active and sense the data channel for 8 ms after sleeping for a period of time (e.g., 135 ms, 115 ms, 95 ms, 75 ms, 55 ms and 35 ms). The energy consumption model is established based on the measurement results presented in [21]. In particular, the current for transmission is 8.5 mA, while it is 7.0 mA for reception. For LWOF, the signal radio consumes about 100 μA current when the node powers down the data radio.

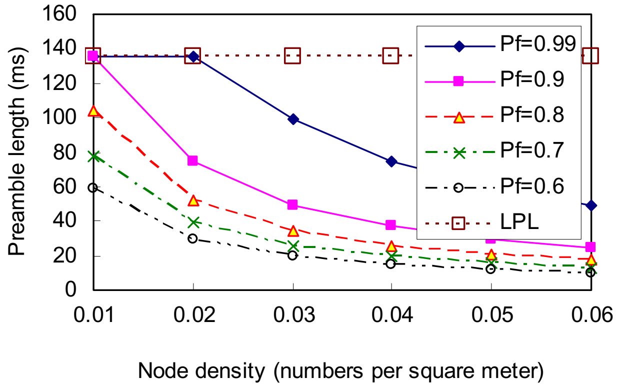

Fig. 4. Relationship between the preamble length and the node density for LWMAC with different forwarding probabilities

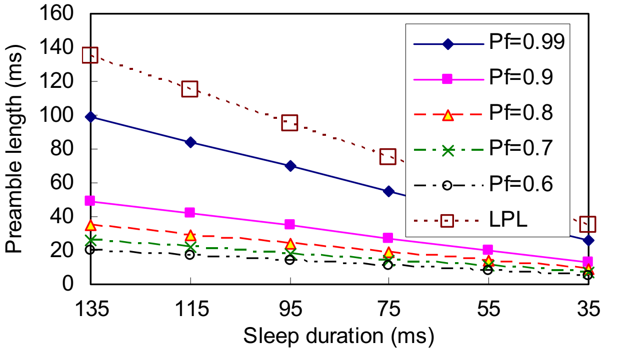

Fig. 5. Relationship between the preamble length and the sleep duration for LWMAC with different forwarding probabilities

We specify the two nodes, which lie at the two ends of the diagonal of the region, as the data source and the sink, respectively. The source generates a packet of 36 bytes every one minute, and runs for 24 hours. The radio range of each node is 20 meters, so the expected distance from the source to the sink is about 7 hops. The maximum data rate of the data channel is 19.2 Kbps.

We evaluate the following three protocols, namely OF, LWOF with the LPL MAC protocol (LWOF-LPL), and LWOF with the LWMAC protocol (LWOF-LWMAC) in terms of the following metrics.

1) Packet delivery ratio: the number of packets received by the sink divided by the number of packets transmitted by the source.
2) Latency: the average delay required in forwarding a packet from the source to the sink.
3) Normalized energy consumption: the total energy consumed when the simulation ends divided by the number of packets received by the sink.

For LWOF, the expected forwarding probability (P_f defined in Equation 2) is 0.9. Results shown in this section are averages over five runs of simulation with different random seeds.

Figure 6 shows the packet delivery ratios of different forwarding schemes for the sensor networks with different duty cycles. We can see that LWOF-LPL has the highest packet delivery ratio, since it employs a sufficiently long preamble to guarantee the successful reception of packets by the next hop. However, the long preamble incurs longer latency and more energy consumption, as shown in Figure 7 and Figure 8, respectively. Due to the inaccuracy of the historical information about the neighbors' duty cycles, some packets may be lost by the intermediate nodes when employing the OF scheme. As expected, the packet delivery ratio of LWOF-LWMAC is about 0.9.

As shown in Figure 7, the long preamble employed in LWOF-LPL causes a significant transmission delay, while it is much smaller for LWOF-LWMAC due to the reduced preamble length. Since OF does not employ preamble, the average packet delay is smaller than that of LWOF-LWMAC. However, the forwarding principle (i.e., random walks) of OF may lead to higher latency than LWOF-LWMAC in some scenarios.

As shown in Figure 8, the long preamble employed in LWOF-LPL results in much more energy consumption for transmitting each packet. For OF, extra energy are consumed in periodic exchanges of duty cycling information, and it is less energy-efficient than LWOF-LWMAC.

The above findings from our simulations show that our proposed light-weight opportunistic forwarding (LWOF) protocol, along with the energy-efficient MAC protocol (LWMAC), can provide reliable service of data delivery with less energy consumption.

V. CONCLUSION AND FUTURE WORK

In this paper, we propose a light-weight opportunistic forwarding (LWOF) scheme to mitigate the impact of highly dynamic topology (mainly due to the asynchronous duty cycle) on reliable data delivery in wireless sensor networks. Differing from other recently proposed schemes, LWOF neither employs historical network information nor a contention process to select a forwarder prior to data transmissions. It takes advantage of the preamble in LPL MAC protocols and dual-channel communication to remove the overhead of making a forwarding decision prior to data transmission.

Along with the light-weight opportunistic forwarding, we propose an energy-efficient MAC protocol (LWMAC) with a shortened preamble, by exploiting the non-deterministic characteristics of opportunistic forwarding. The preamble length in LWMAC is a function of the node density and node sleep duration.

Simulation results show that LWOF, along with LWMAC, can provide reliable service of data delivery with less energy consumption.

In the future, we will evaluate the performance of our proposed protocols for mobile sensor networks.

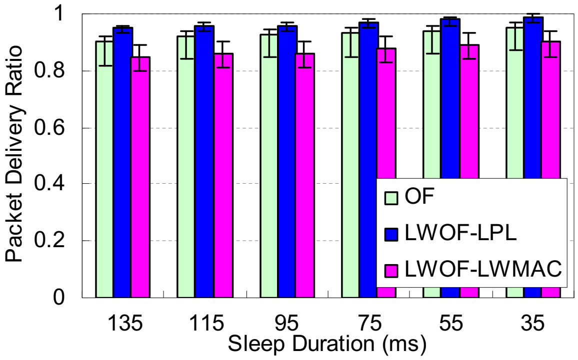

Fig. 6. Packet delivery ratio of different forwarding schemes for sensor networks with different duty cycles

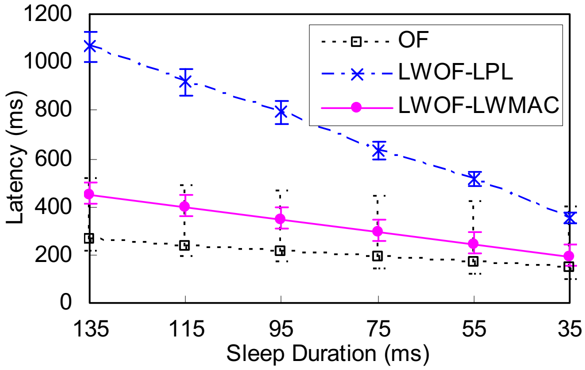

Fig. 7. Latency of different forwarding schemes for sensor networks with different duty cycles

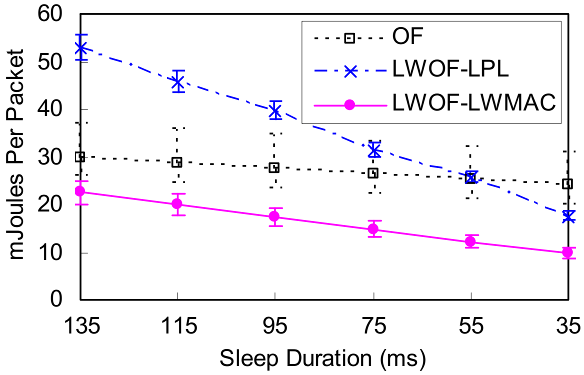

Fig. 8. Normalized energy consumption of different forwarding schemes for sensor networks with different duty cycles

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