DEPEND: DEnsity adaptive Power Efficient Neighbor Discovery for wearable body sensors

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Abstract— **Wearable sensors are designed to monitor the individual user's activities or the social behaviors within a group. Due to the nature of their applications, the wireless transmission of the sensory data are subject to extremely stringent energy constraints. Also, due to user mobility, the network topology is frequently changing. Therefore, the design of efficient communication protocols for wearable sensor networks is technically challenging. As a fundamental building block of the communication protocol, the power-efficient neighbor discovery mechanism is important for the network to function well. We propose an asynchronous neighbor discovery algorithm, namely, DEPEND (Density-based Power Efficient Neighbor Discovery), which requires neither time synchronization nor carrier sensing, and thus is easy to implement on low cost hardware. DEPEND exploits traditional Quorum-based Power-Saving (QPS) scheme, and incorporates an adaptive mechanism to respond to dynamic node density so as to improve and balance the performance of power saving and neighbor discovery. Each DEPEND-enabled network node calculates the local node density and forecasts the probability that new neighbors enter its communication-range in the near future, and adjusts itself to the most suitable QPS mode to discover new neighbors. Analytical and experimental results show that DEPEND is able to improve the neighbor-discovery performance without consuming much more power, thus the discovery performance and the power efficiency are jointly enhanced.**

I. Introduction

Recently, the application of wearable sensors to monitor people's individual activities and social behaviors has attracted a lot of interest. The market trends also indicate that users are ready for wearable body sensor products such like step counters, heart-rate bands, blood pressure monitors, that constitute a networked body sensor system that sends their activity and health data to a backend server for analysis [1]. Even more aggressively, experimental wearable sensor systems [2] have been deployed in office buildings to collect the information of people's social behaviors, such as vocal level, body movements and inter-person encounters, and the analysis of the data collected is expected to help people improve their work productivity and even their level of satisfaction.

However, the stringent energy limitations of wearable sensors makes the communication protocol design very challenging. A practical wearable sensing system would require a sensor to transmit the data back to the server over a lifecycle of several weeks before the sensor runs out of battery. Another challenge for wearable sensor network protocol comes from the rapidly changing topology and the distributed nature of the network. Although in body sensor network applications, the node does not need to relay sensory data to the base station, timely discovery of neighbors are still necessary and important. For instance, sensor nodes need to discover adjacent data collecting point in order to upload sensory data. Also in aforementioned social sensing applications, where people's proximity serves as the metric of social interactions, neighbor discovery itself becomes a sensing method. The distributed nature of the body sensor networks render big challenges to accurate time synchronization amongst nodes, which makes the protocol designs more difficult.

Fortunately, one can take advantage of the solid foundations of the existing research of Mobile Ad hoc Network (MANET) [3], which shares similar characteristics of limited energy and changing topology with wearable sensor networks, as a reference for wearable body sensor network protocols. In MANET, a node has two working phases, namely, the neighbor discovery phase and the data transmission phase. When the network is sparse and with rapidly changing topology, as in most case of the wearable body sensor networks, the portion of time that a node spend in the neighbor discovery phase is very high, making the energy consumption of the neighbor discovery phase dominate the total power budget. Unlike typical MANETs in which cell phones and tactical radio stations are communication nodes, wearable body sensors use low-power radio transceivers whose listening power is comparable to the transmission power. Therefore, energy optimization shall consider reducing channel listening time as well as the transmission time, and this invalidates the power efficiency of the traditional MANET neighbor discovery methods of eavesdropping the channel to discover neighbors.

Another helpful field is the wireless sensor network (WSN), which features low-cost radios, energy constraints, and distributed nature. However, since most WSN protocol research assumes quasi-static and connected topology, the energy efficiency study was often focused in data transmission phase[4][5][6][7], and the energy efficiency for the neighbor discovery phase has been overlooked.

Many proposed power-saving protocols demand synchronous clocking. For example, PSM [8] is the classical power-saving protocol on the MAC layer. It maintains a synchronous wake-up scheme, and each node can periodically go to sleep mode to reduce power. The need for synchronous

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nodes is a challenge in MANET. To solve this problem, some asynchronous power-saving protocols [9] have been proposed. In these protocols, the quorum-based protocol (QPS) is a simple but effective solution. It divides the time into intervals and organizes them in groups, not necessarily synchronized. In each group, some intervals will be selected for nodes to sleep to save energy. QPS enjoys lower energy consumption in the phase of neighbor discovery at the cost of longer delay and some level of neighbor missing.

In this paper, based on the asynchronous QPS protocol, we propose an adaptive wake-up strategy (DEPEND) which is suitable for the wearable body sensor networks. DEPEND requires each node to perform a dynamic QPS scheme which is adapted to the local network density. Specifically, each node estimates the local node density by the number of its current neighbors and forecasts the probability of encountering new neighbors in the next time interval and chooses a suitable wake-up sequence. By carefully design of the forecasting and scheme adapting, we increase the efficiency of power-saving and reduce the delay and neighbor missing probability simultaneously.

The remainder of the paper is organized as follows. First we review and comment on some existing power-saving protocols using wake-up strategies in Section II. In Section III, we introduce the neighbor encounter probability forecasting model, and then introduce the D-QPS mechanism based on the model. In Section IV, we analyze the performance of the proposed protocols, and the simulation results are evaluated in both virtual and realistic mobility models, respectively. Finally, Section V draws the conclusion to this paper.

II. Related Work

IEEE 802.11 PSM [8] proposes the node wake-up mechanism as a power-saving solution, with the node's states in one of the two modes, namely, the active mode and the sleep mode. Most of the energy budget is consumed in the active mode while transmitting and receiving packets, or even listening to the channel. 802.11 PSM maintains a synchronous timing sequence to control all the nodes in the network to wake-up at the same time periodically, so they can discovery each other and decide if it is necessary to resume activity and transfer data, or go to sleep until the next wake-up signal. 802.11 PSM can save much energy. However its performance depends heavily on the synchronization, thus only suitable for fully connected networks.

To balance the energy efficiency and throughput of networks, some adaptive MAC protocols have been proposed. PMAC [6] and A^2FMAC [10] maintain the wake-up schedules for a node based on its traffic demands and its neighbors. They can get a better throughput in heavily loaded network and save more energy when the load is light. But this requires frequent switching between sleep and wake-up states. DPSM [11] makes each node chooses its wake-up window size dynamically, which enhances throughput and energy efficiency.

More suitable for distributed dynamic networks, asynchronous mechanisms [12] do not require clock synchronization and each node follows its own wake-up schedule. These protocols work well when a central control is costly or impossible. In this case, two nodes can communicate only when their active windows overlap, which needs the node wake up more frequently.

Quorum-based Power-Saving (QPS) protocol was firstly proposed in [9] as a solution for asynchronous wake-up protocols. Nodes in QPS schedule their wake-up time by an asynchronous mechanism (called Quorum). Each node divides the time into equal-length beacon intervals, and l (called $cycle\ length$) intervals are grouped together as the scheduling cycle. A quorum pattern is defined for each cycle to control node's wake-up behaviors. Many quorum systems have been proposed to define the cycle pattern in QPS, for instance, the grid quorum system [13], the cyclic quorum system [14], the tree-base quorum system [15] and so on.

To balance the energy efficiency and throughput and to extend the network's lifetime, AQEC [7], AAPM [16], EACDS [17], MQB [18], Traffic-Aware QPS [19] have been proposed as adaptive QPS protocols. In these protocols, nodes choose different quorum systems by their own traffic or surplus energy. Since these protocols are adaptive to the traffic, they are able to save more energy when traffic is light and to reduce the delay when traffic is heavy. With consideration of the surplus energy, the network's lifetime can be extended.

All the MAC layer power-saving protocols save the energy of the nodes by turning them into sleep mode. However, in MANET, nodes are mobile and the network topology is changing. Each node needs to update its neighbor list to guarantee the functioning of the network. Naturally, the longer for nodes stay in sleep mode, the higher probability of its neighbors being missed. Some of the above protocols are adaptive to traffic to reduce the delay of data transmission. But none of them considers the performance in neighbor discovery. As discussed before, the neighbors discovery task will demand a significant share of the total energy budget and thus cannot be overlooked. Moreover, the performance of neighbor discovery is also important for wearable sensor networks. Therefore, we shall consider the performance-energy tradeoff carefully.

III. Density adaptive Power Efficient Neighbor Discovery

DEPEND (Density adaptive power efficient neighbor discovery protocol) is a power-saving MAC protocol, and its design rationale is based on the traditional QPS protocol but introduce dynamic neighbor number prediction. This protocol focuses on the process of neighbor-discovery phase, and reduces the energy cost by decreasing the cost of channel monitoring and probing. Under this protocol, a node firstly estimates the local network density, then estimates the probability of encountering new neighbors in the next time interval. According to the estimation, the node chooses a suitable wake-up strategy.

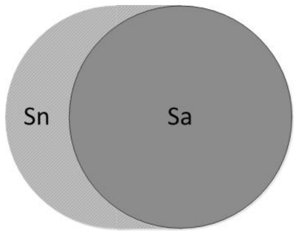


Fig. 1. Newly covered area between two serial intervals

A. Neighbor Number Prediction

In DEPEND, a node needs to forecast the encounter probability of new neighbors with the current local network density. We define some notations as follows. v is the speed of the mobile nodes; R is the radio communication range of the node; t is the length of the interval. And we assume the nodes are homogenous, i.e., this three elements are same and constant for every nodes in the network.

For wearable sensors, we make some system assumptions for neighbor forecasts:

Assumption 1. The speed of the mobile node is moderate, which means $vt \ll R$. Otherwise, nodes will be too quick to be discovered.

Assumption 2. The node density is slowly varying in time and space, which guarantee that the node density will not change dramatically in a few intervals as node moves. This assumption can be made because the neighbor density is changing incrementally by the moderate movement of nodes.

Assumption 3. The nodes in a node's small adjacent area are subject to a uniform distribution. This assumption is made because the slowly varying space assumption and uniform spatial distribution is the best guess one can make when there is no knowledge of the local distribution.

In each interval, the area covered by the node's radio range is:

$$S_a = \pi R^2. \tag{1}$$

For the next interval, the newly covered area is calculated as

$$S_n = 2\pi R v t, \tag{2}$$

assuming that there are n_a neighbors in the area of S_a, due to the assumption 3 that the nodes are subject to uniform distribution. Furthermore, based on Assumption 2, the probability of n nodes locating in the newly covered area is:

$$p(n) = \binom{n_a}{n}(\frac{s_n}{s_a})^n(1-\frac{s_n}{s_a})^{n_a-n}. \tag{3}$$

Moreover, the number of nodes in S_a can be calculated as:

$$n_a = ds_a, \tag{4}$$

where d is the local node density of the network.

So the probability of at least one node enter the newly covered area is calculated as follows:

$$P = 1 - p(0) = 1 - \binom{n_a}{0}(1-\frac{s_n}{s_a})^{n_a} = 1 - (1-\frac{2vt}{R})^{\pi R^2 d}. \tag{5}$$

As shown in Equation (5), the probability of at least one node entering the newly covered area in the next interval is related to the speed, the radio range of the node, and the local network density.

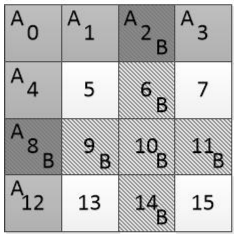
B. Energy Cost, Delay and Neighbor Missing Probability of QPS

QPS is a widely used asynchronous protocol for MANET. In QPS protocols, each node divides the time into equal-size intervals, which are grouped into cycles of l intervals. The intervals are classified into two types: active interval and power-saving interval. When in active intervals, a node broadcasts its beacon within a beacon window and remains active for data transmission. While in power-saving intervals, a node stays active for a very short time and sleep if there is no transmission.

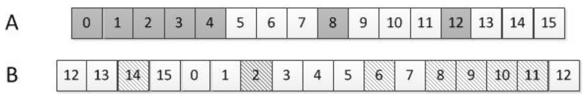
A node maintains its wake-up sequence by a principle called quorum system. Nodes with the same quorum system and cycle length l satisfy the demand that no matter how asynchronous the clocks are, a node always has at least one beacon windows that are fully covered by another node's active period in every l consecutive beacon intervals. A node in an active interval broadcasts its beacon within the beacon window using a random back-off mechanism and its active neighbors will discovery it by hearing the beacon. Collision probability between beacons is very low as beacon transmissions are very short. [7][16][17][18] show and prove that nodes with different cycle length can discover each other within finite time if they use a suitable quorum system. The mutual discovery between two neighbors needs both of them to be active.

To illustrate the QPS system, a grid-QPS is shown in Fig.2(a), where the entire time duration is divided into groups of 16 intervals. Each node randomly selects a full row and a full column of the grid system to be active. Fig.2(b) shows, node A can hear B in interval 1 and 12, while on the contrary, node B can hear A in interval 8 and 14.

In order to ensure at least one overlap between each pair of nodes, a QPS with a cycle length l (named l-QPS) needs at least $\lceil \sqrt{l} \rceil$ active intervals in each cycle length, which is proved in [20]. An l-QPS that reaches this bound achieves the optimal energy efficiency performance. Thus the Active Interval Ratio (AIR) of an optimal l-QPS, which is able to reflect the energy cost, can be calculated as (6). As the only overlap active interval subjects to uniform distribution within the cycle length, the average delay of neighbor discovery is (7). And in MANET, if two nodes have no overlaping active intervals within the time duration when they are reachable to each other (such as N intervals), they are not able to discover each other, causing a neighbor missing. The missing probability within N intervals (P_{Nm}) is calculated



(a) *Grid System*



(b) *Overlap in Grid – QPS System*

Fig. 2. Grid-QPS mechanism

as (8). In this equation, P_{No} is the probability of two nodes having at least one overlap within N intervals, and can be statistically computed in terms of specific QPS strategies.

$$AIR = \frac{\left\lceil \sqrt{l} \right\rceil}{l}, \tag{6}$$

$$Delay = l/2, \tag{7}$$

$$P_{Nm} = 1 - P_{No}. \tag{8}$$

Table I shows the performance of QPS with different cycle length. The data are calculated by (6), (7), (8) under different QPS strategies. It shows that larger cycle length saves more energy, but the performance of delay and neighbor missing is worse as well.

TABLE I
ENERGY COST, DELAY AND MISSING PROBABILITY OF QPS

l-QPS	AIR	Avg Delay	missing probability within N intervals						
			N=1	2	3	4	5	6	7
1-QPS	1	0	0						
3-QPS	$\frac{2}{3}$	$\frac{3}{2}$	$\frac{5}{9}$	$\frac{2}{9}$	0				
5-QPS	$\frac{3}{5}$	$\frac{5}{2}$	$\frac{16}{25}$	$\frac{8}{25}$	$\frac{4}{25}$	$\frac{2}{25}$	0		
7-QPS	$\frac{3}{7}$	$\frac{7}{2}$	$\frac{40}{49}$	$\frac{30}{49}$	$\frac{25}{49}$	$\frac{18}{49}$	$\frac{12}{49}$	$\frac{1}{7}$	0

C. Density adaptive Power Efficient Neighbor Discovery protocol

Under traditional QPS protocols, nodes share the same quorum system of same cycle length l. To get a better performance of neighbor-discovery and power-saving, we propose to incorporate density as a dynamic parameter into a quorum system, and design the Density adaptive Power Efficient Neighbor Discovery protocol (DEPEND). In DEPEND, nodes choose a large cycle length when the local network density is low, to save extra energy, and choose a small one to get a better performance on neighbor-discovery when the density is high. By balancing energy cost and the performance of the neighbor discovery (delay, neighbor missing), network performance can be enhanced.

In DEPEND, a node selects its cycle length according to the local network density as follows:

1) If the node is in sleep state in the current interval, the cycle length is kept.
2) If the node is active in the current interval, it gets the beacon frames from its neighbors which are also active. So it acknowledges the number of active neighbors (N_{an}) around it, reflecting the local network density. Then the node calculates the probability of encountering new neighbors in the next interval P and chooses a suitable cycle length.

In order to select the proper cycle length, four density thresholds are defined for node based on the common l-QPS, shown as:

$$P > threshold_1 \rightarrow 1 - QPS \tag{9}$$

$$threshold_1 \geq P > threshold_2 \rightarrow 3 - QPS \tag{10}$$

$$threshold_2 \geq P > threshold_3 \rightarrow 5 - QPS \tag{11}$$

$$threshold_3 \geq P \rightarrow 7 - QPS \tag{12}$$

The more neighbors a node discovered in current interval, the higher local density can be expected. Therefore, based on (5), higher local density means higher probability of encountering new neighbors in the next interval, and the node is required to be more frequently active to avoid missing a neighbor.

To determine whether to be turned in to sleep or active states, the node needs to be aware of the overlap probability of the next interval. Therefore, as shown in Table I, the value $N = 1$ is selected to calculate the overlap probability, which is be used as the threshold in DEPEND.

$$threshold_1 = P_{1o}^{3-QPS} = 4/9 \tag{13}$$

$$threshold_2 = P_{1o}^{5-QPS} = 9/25 \tag{14}$$

$$threshold_3 = P_{1o}^{7-QPS} = 9/49 \tag{15}$$

Assume that active nodes determine their cycle lengths and the next interval states before the end of the current interval, and the sleeping nodes maintain their current strategy determined before being turned into sleep mode. When a node is in the m-th interval of the l cycle, which is decided by its current QPS strategy, the process of determining the action of the next interval is:

IV. PERFORMANCE EVALUATION

We conducted simulations to evaluate the performance of DEPEND in Matlab. We only consider the neighbor discovery phase, which is the focus of this work.

We set up the simulation scenarios as follows. A virtual network is composed of nodes unevenly distributed in a

Input: Current cycle length l,current interval number m

begin

  if *node is sleep* **then**

    $l \leftarrow l$;

    $m \leftarrow m + 1$;

  end

  if *node is active* **then**

    broadcast beacon at the beginning of the interval;

    $P = 1 - (1 - \frac{2vt}{R})^{N_{an}}$;

    $l \leftarrow$ new l by Equation(8-14);

    $m \leftarrow m + 1$;

  end

  determine the state of the next interval by the mechanism of $l - QPS$;

end

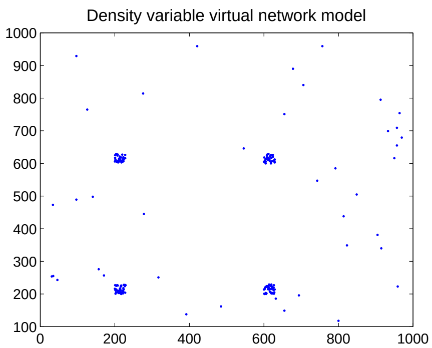


Fig. 3. Heterogeneous Node Density

1000 × 1000 area, as shown in Fig.3. Specifically, there are four areas with higher node density representing higher activity intensity, such as a meeting room or a workplace, the rest are areas with lower node density. A mobile node with DEPEND moves in the area for a time.

We compare the performance of DEPEND with four non-adaptive quorum systems, namely 1-QPS, 3-QPS, 5-QPS, and 7-QPS. The performance metrics are detection delay, missing probability, and energy consumption, evaluated as a function of node's communication range.

Fig.4 shows that DEPEND enjoys smaller average delay of neighbor discovery than all the traditional QPS protocols, except the constantly active 1-QPS system in which zero delay is expected. For example, the average delay of DEPEND is only 0.1t when the detection range is 25, which is only 25% that of 5-QPS and 15% that of 7-QPS.

Fig.5 shows that DEPEND also enjoys a smaller missing probability of neighbor discovery than others except the constantly active 1-QPS system. As the transmission range becomes larger, the missing probability and detection delay gets smaller, which is because a bigger transmission range causes a longer contact period time, so nodes have more time to discovery each other and detect each other more frequently in their contact duration. When the transmission range is 25,

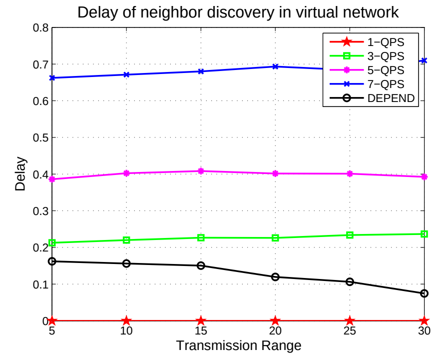


Fig. 4. Delay of neighbor discovery

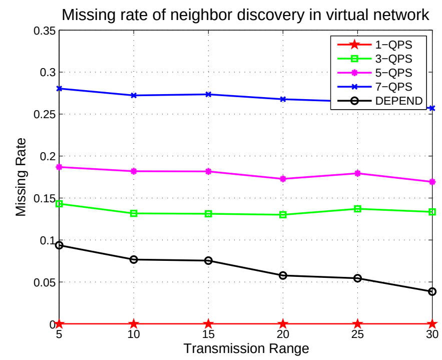


Fig. 5. Missing rate of neighbor discovery

the missing probability of DEPEND is about 36% that of 3-QPS and 18% that of 7-QPS.

Fig.6 shows the energy consumption of all the protocols. DEPEND's power consumption increases with the transmission range. There are two reasons. One, higher transmission range requires more transmit power. Two, as indicated by (6), the probability of encountering new neighbors increases with the transmission range, so nodes adapt to more active QPS system, and then the energy cost becomes bigger. It is shown from the result that when the transmission range is moderate, DEPEND can enjoy a good performance with reasonable energy consumption.

To sum-up, DEPEND can get a smaller delay and missing

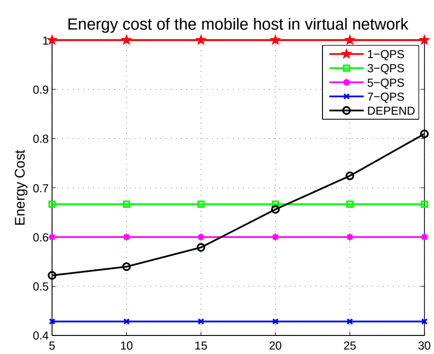


Fig. 6. Energy cost of the mobile node

probability of neighbor discovery than the traditional QPS when node density heterogeneity is presented. Meanwhile, its energy cost can also smaller than that of others with a moderate transmission range. For example, when the transmission range is 15, the energy cost of DEPEND is smaller than that of 5-QPS, but its delay is only 37% that of 5-QPS and the neighbor missing rate is about 24% that of 5-QPS. The balance between performance and energy consumption can be fine-tuned by changing the transmission range and the aggressiveness of quorum system adaptation in the protocol. For wearable sensor systems of stringent energy constraints and mobility nature, DEPEND is a reasonably suitable solution for neighbor discovery.

V. Conclusion

The smart wearable body sensors require energy-efficient protocols. The trade-off between the performance of protocol and the energy efficiency needs to be carefully considered. In most application scenarios for wearable body sensor networks, the node density is unevenly distributed spatially. In this paper, based on the traditional QPS protocols, we proposed a new power saving neighbor discovery protocol, DEPEND, with considering variable node densities. DEPEND nodes are able to forecast the probability of contacting new neighbors, and then select the suitable QPS mode to balance the energy consumption and the network performance, such as detection delay and missing rate. The simulation results show that, compared to traditional QPS protocols, DEPEND is able to save more energy and have better performance in neighbor discovery.

It is worth noting that, in DEPEND, the probability of contacting new neighbors is calculated based on linear prediction of node motion, and the assumption of the uniform node distribution in an adjacent area is sometimes circumscribed. We plan to exploit more sophisticated model such like the particle filter [21] [22]to improve the accuracy and fitness to more general node mobility models.

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