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지연 제한 무선 센서네트워크를 위한 기회적 전송

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Opportunistic Transmission for Wireless Sensor Networks under Delay Constraints

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요 약

이 논문에서는 에너지 제한이 엄격한 환경에서 동작하는 무선 센서 네트워크를 위한 기회적 전송 전략을 제안한다. 본 연구는 무선 센서 네트워크의 호스트 지연에 민감한 어플리케이션을 고려하였다. 우리가 제안한 전송 전략은 시변 채널에서 지연의 제약을 받으면 채널상태가 좋을 때 전송을 시도하는 이진-결정 기반 전송 방식이다. 마코브 결정 프로세스가 전송 결정을 위한 최적 임계치를 찾는데 사용되었다. 우리의 이진-결정 기반 전송 방식은 에너지 소모의 원인인 전송실패를 가능하면 피하기 위해 채널의 질이 최적 임계 치를 넘을 때만 전송을 시작한다. 우리가 제안한 방식의 성능을 검증하기 위해 무선 페이딩 채널에서 광범위한 시뮬레이션을 수행하였다. 시뮬레이션 결과는 이진-결정 기반 전송 방식이 다른 방식보다. 35% 높은 에너지 효율을 가지고 이로인해 네트워크 수명이 연장된다는 것을 보여준다.

1. Introduction

Wireless sensor networks (WSNs) are low-cost communication networks that contain a large number of sensor nodes with limited energy [1]. Since the WSN may function until a significant fraction of sensor nodes are operational, energy efficiency is a key technical issue in the design of WSN [2{4]. Especially, careful management of energy resources is required to maximize the lifetime of the WSN [5]. The sensor nodes may operate over the time-varying wireless channel whose quality significantly fluctuates over time due to fading and interference. Such time-varying nature of wireless channel imposes many constraints in designing an energy-efficient transmission scheme. For instance, a transmission attempt, when the wireless channel is temporarily bad, is highly likely to be failed and may lead to a waste of energy. To avoid this, the sender may wait until the channel becomes better. However, deferring the transmissions until the channel becomes better may cause a longer latency. This is a trade-off problem between energy efficiency and latency. Thus a suitable transmission scheme for the WSNs must be able to adapt to variation of the wireless channel while maintaining a good balance between these two conflicting goals.

In order to improve energy efficiency for WSNs, many different techniques have been recently proposed. Ci et al. in [6] proposed an adaptive adjustment of frame size that is predicted via the extended Kalman filter. In [7], a transmission scheme adopting multicast Ready-to-Send (RTS) and priority-based Clear-to-Send (CTS) was proposed to prioritize the terminal with a good channel in terms of channel access. In [8], the authors obtained an optimal solution of the problem of bu®er and channel adaptive transmission for maximizing system throughput. The Receiver Based Auto Rate (RBAR) protocol in [9] allows the receiver to choose the data rate based on the signal-to-noise ratio (SNR) of the RTS packet. In this paper, we consider an opportunistic transmission strategy for wireless sensor networks hosting delay-sensitive applications. This paper is an extension of our earlier work [10] that took into account the WSNs without delay constraint. Our transmission scheme named binary-decision based transmission (BDT) basically takes an opportunistic transmission approach in which transmissions are attempted only under good channel conditions whenever possible. In the BDT scheme, whether to initiate transmission or not is determined according to the current channel conditions. By exchanging the control messages, e.g., RTS and CTS in 802.11 standard, for channel measurement and associated feedback, the receiver can measure the channel quality and the sender can retrieve such information piggybacked in the return message. To continuously monitor the channel condition, data message and its acknowledgement message are also used to measure and piggyback the channel information. In the BDT scheme, the MDP formulation [12] is used to obtain the optimum threshold for successful transmission. Extensive simulations are performed with ns-2 to verify the performance of our proposal over wireless fading channels. Our transmission algorithms are applied to IEEE 802.11 Distributed Coordination Function (DCF) standard with some necessary modifications [11]. The simulation results show that the use of binary-decision based transmission significantly improves energy efficiency with respect to the plain IEEE 802.11 while satisfying delay requirements.

2. System Model

Our transmission schemes are implemented on IEEE 802.11 DCF standard with some necessary modifications. The modifications are associated with channel measurement and a mechanism for its feedback. In this model, RTS/CTS and DATA/ACK messages are all used in pair for continuous channel monitoring and feedback of the measurement results. Although 802.11 MAC protocols may not be suitable for WSNs, we employ it in this work to demonstrate effectiveness of our transmission schemes. Since our schemes require only exchange of short control messages or piggybacking channel-related information in normal data messages, they are readily applicable to different MAC protocols other than IEEE 802.11 DCF protocol.

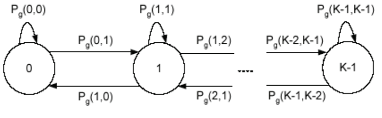

Fig. 1. Finite-state Markov channel model.

A finite-state Markov channel (FSMC) model is used to capture the time-varying behavior of wireless fading channel as shown in Figure 1. The parameters of the Markovian channel can be obtained by using the techniques in [13].

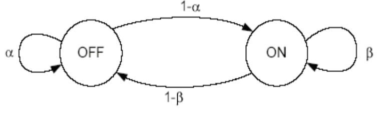

Fig. 2. On-off traffic model with transition probabilities α and β.

We assume that the traffic model is a discrete time on-off source with parameters α and β as shown in Fig. 2. Over time the traffic model alternates between ON and OFF state whose periods follow independent geometric distributions, respectively. Arrival of frame (or packet) occurs each time slot during the ON period only. Delay sensitivity of traffic is modeled by imposing the lifetime of D time slots on each frame. This implies that a frame staying in the buffer longer than D time slots must be dropped. In our analysis, we investigate the impacts of such delay constraint on system throughput. To consider the applications that require up-to-date sensing data under light traffic load, we assume that the buffer can hold at most one frame. Thus any new coming frame preempts the existing one and the existing frame is dropped.

3. Binary-Decision Based Transmission

In our proposed scheme the sensor node takes either of two actions: *Transmit* and *Defer*, corresponding to transmitting the data and deferring the transmission, respectively. The current wireless channel is measured at the receiver via RTS or Data frame, and is classified into one of two states including *Good* and *Bad* based on the received SNR. This information is notified back to the sender by embedding it in the return frame, i.e., CTS or ACK frame. The SNR threshold used to classify the channel states is determined using the Markov decision process (MDP) as explained later in detail. Figure 3 depicts the BDT scheme with RTS/CTS exchange.

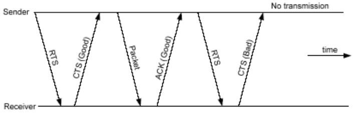

Fig. 3. Binary-decision based transmission.

The problem of finding the optimum thresholds for successful transmission is formulated using the MDP. The optimum operation policy in terms of energy efficiency is obtained. For the sake of tractable analysis, it is assumed that time is divided into time slots of equals length of T_f seconds. It is also assumed that the outcome of transmission is immediately available at the end of transmission.

System States We denote the set of possible system states by S in which S is a finite set. The system state si at time slot i is given by

$$s_i = \langle g_i, t_i \rangle$$

where gi is the channel state at time slot i, $0 \le g_i < K$, and t_i is the state of sensor node at time slot i. The possible states of the sensor node include *Idle* and (D + 1) *Busy* states where D corresponds to the lifetime of frame. Let I, and B_k (k = 0, 1, $\cdots\Leftrightarrow$ D) denote *Idle*, and *Busy* states, respectively. The sensor node is said to be in kth *Busy* state (denoted by B_k) when a frame is delayed by k time slots and in *Idle* state when no frame is present.

Control Actions Depending on system state s_i, sensor node determines to transmit or to defer transmission. Let $A(s_i)$ denote the set of all possible control actions in state s_i. a_i is the control action executed at time slot i. Each action in $A(s_i)$ corresponds to the following values:

$$a_i = \begin{cases} 0, & \text{Defer} \\ 1, & \text{Transmit} \end{cases}$$

Cost of Actions Given the system state s_i and a control action a_i, the immediate cost incurred in time slot i is defined as

$$C_i(s_i, a_i) = L_e(g_i, a_i)P_t + \delta L_d(s_i, a_i)$$

where P_f (g_i) is the frame error rate when the channel state is g_i. Assuming independent bit errors, the frame error rate P_f (g_i) for frame size L and the channel state gi is given by

$$P_f(g_i) = 1 - (1 - P_b(g_i))^L$$

where $P_b(g_i)$ is obtained from (1). $L_d(s_i, a_i)$ is given by

$$L_d(\langle g_i, B_k \rangle, a_i) = \begin{cases} \beta((1-a_i) + a_i P_f(g_i)), & k = 0 \\ (1-\alpha)((1-a_i) + a_i P_f(g_i)), & 0 < k < D \\ (1-a_i) + a_i P_f(g_i), & k = D \end{cases}$$

System Dynamics Given the system state s_i = ℜg_i,t_i ⊤ and a control action a_i, the probability of the system being state s_{i+1} = ℜg_{i+1}, t_{i+1}> in next time slot is:

$$\Pr[s_{i+1} = \langle g_{i+1}, t_{i+1} \rangle \mid s_i = \langle g_i, t_i \rangle, a_i = a] = P_g(g_i, g_{i+1}) P_t(t_i, t_{i+1}, a)$$

where $P_g(g_i, g_{i+1})$ is the transition probability from channel state g_i to g_{i+1} and $P_t(t_i, {}_{ti+1}, a)$ is the transition probability of sensor node state from t_i to t_{i+1} under the given control action a. Figure 4 depicts the state diagram of the behavior of sensor node in which the transition probability $P_t(t_i, t_{i+1}, a)$ is provided.

Average Cost Let $\pi = \{\mu_0, \mu_1, \mu_2 \ldots\}$ be a policy which maps system states into control actions. Our objective is to minimize over all policies π with μ_t : S→A, $\mu_t(s) \in A(i)$ for i and s, the average cost per stage

$$J_\pi(s) = \lim_{T\to\infty} \frac{1}{T} \left\{ \sum_{i=0}^{T-1} C(s_i, \mu_i(s_i)) \mid s_0 = s \right\}$$

We need to choose an optimal policy π to minimize this cost:

$$\pi^* = \arg\min_{\pi} J_\pi(s)$$

Our model is an unichain MDP model in which its stationary policy and optimal average cost can be obtained by using the relative value iteration algorithm in the dynamic programming techniques [8][14].

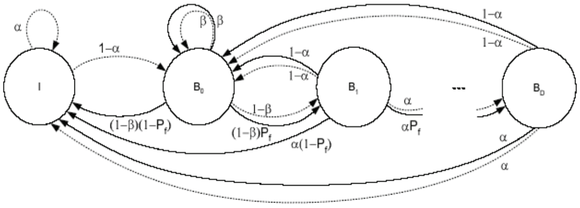

Fig. 4. State diagram of the BDT scheme. Solid line indicates the transmit action whereas dotted line does the defer action.

4. Numerical Results and Simulations

We consider 30 sensor nodes randomly dispersed over a network field (350m×350m) and 1 sink node. Only 15 sensor nodes generate a frame of 128 bits destined to the sink node and the rest of the sensor nodes only relay the frames to the sink node. The on-off traffic model is used to generate the traffic. Wireless fading channel is modeled by 20-state Markov chain model. Table 1 summarizes the values of the various parameters used in our experiments. Note that T_f in our simulation is configured to match the period in which sending and receiving nodes complete the exchange of RTS, CTS, DATA, and ACK frames using RTS/CTS mechanism. Besides the additive parts of 802.11 such as IP header and MAC header are tripped off in our simulations.

Table 1. Parameter values used in the simulations and numerical results.

Parameters	Value (default)
Number of sensor nodes	30
Mobility of sensor nodes	Stationary
Frame transmission time (T_f)	1 ms
Transmission range of sensor node	150 m
Source rate during "ON" state	128 Kbps
Routing protocol	DSDV
Doppler frequency	10 Hz
On-off source traffic parameters α	0.95
On-off source traffic parameters β	0.25
Lifetime of the frame (D)	$100 \cdot T_f$
Weighting factor in cost function (δ)	0.1

We first analyze how the optimum threshold for transmit action varies under different channel conditions.

Figure 5 shows the optimum transmit threshold in dB of BDT, for varying Doppler frequency (f_m) and frame lifetime (D). As shown in the figure the optimum values of state B_i tends to increase as Doppler frequency becomes larger. This result indicates that deferring the transmission is more favorable in a fast varying channel. In a slow fading channel, deferring the transmission is not beneficial since the channel will not become better in the near future when the node currently sees bad channel. Thus the threshold should be set to be lower. However, a higher threshold is preferred under fast fading channel to prioritize the defer decision. Another interesting observation from Fig. 5 is the thresholds for B_i, $0 < i \le D$, are higher than B_0 for lower Doppler frequencies. That is because B_0 is in "ON" state in which traffic is generated, thus faster transmission is preferred to avoid buffer overflow.

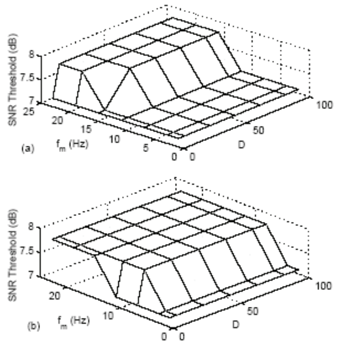

Fig. 5. The optimum thresholds of transmit action versus Doppler frequency and delay constraint ($\rho = 10$dB, $\alpha = 0.95$, $\beta = 0.25$). (a) state B_0. (b) states B_i, $0 < i \le D$.

Figure 6 shows the impacts of traffic load on the optimum threshold for transmit action. As shown in the figure, the thresholds for B_0 decrease when the traffic load becomes heavier. Note that lower α and higher β corresponds to heavier traffic. In contrast, the thresholds for B_i, $0 < i \le D$ are sensitive to β only. This is because the state B_i, $0 < i \le D$ implies that source traffic is in "OFF" state, independent of the probability β of "ON"-to-"ON" transition probability.

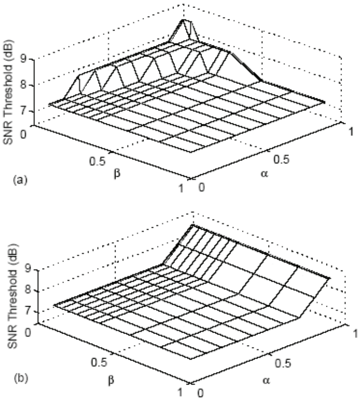

Fig. 6. The optimum thresholds for transmit action versus the traffic parameters α and β ($\rho = 10$dB, $f_m = 20$Hz, $D = 100 \cdot T_f$). (a) State B_0. (b) States B_i, $0 < i \le D$.

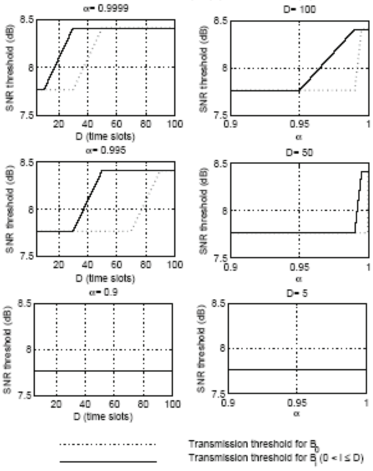

Fig. 7. The optimum thresholds of transmit action versus α and D ($\rho = 10$dB, $\delta = 0.1$, $\beta = 0.05$, $f_m = 20$Hz).

Figure 7 shows the thresholds for transmit action under varying α and delay constraint D. As shown in the figure, the thresholds tend to increase for a fixed α when the lifetime of frame is extended from 5 to 100 slots. To be more precise, this observation seems to be true only for relatively larger values of α. As α becomes smaller, this threshold remains almost constant over $5 \leq D \leq 100$ slots. These results indicate that delay constraint significantly influences the transmit threshold when it is rather shorter than the OFF period. This is somewhat obvious because frame in the buffer will be preempted by new arriving frame when delay constraint is larger than mean OFF period. Thus delay constraint becomes meaningless in this case.

Figure 8 shows simulation results of energy efficiency for two transmission schemes: 802.11 with BDT and plain 802.11. Here the energy efficiency is defined as the ratio of the number of successful transmissions over the number of transmission attempts. As shown in the figure, the 802.11 with BDT and plain 802.11 has the energy efficiency of 0.96, and 0.71, respectively (ρ= 10dB). A significant improvement, more than 35%, is achieved with our proposed scheme, compared with the existing equivalent counterpart. Such energy conservation mostly comes from the reduction in the number of frame loss due to transmission errors. However, such gains do not come for free. As shown in the next figure, our transmission scheme based on the opportunistic transmission sacrifices throughput by deferring the transmission when the channel state is bad.

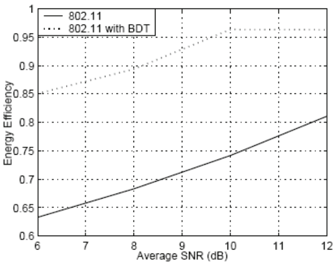

Fig. 8. Energy efficiency of two transmission schemes: 802.11 with BDT, and plain 802.11.

Figure 9 shows throughput of two alternative transmission schemes: 802.11 with BDT and plain 802.11. Throughput is observed at the sink node and averaged over the simulation time. As shown in the figure, plain 802.11 has higher throughput than 802.11 with BDT, although the gap is not significant. As mentioned earlier, a higher energy efficiency can be achieved at the expense of throughput. Considering the trade-off issue, we can see throughput performance of our proposed scheme is not significantly deteriorated.

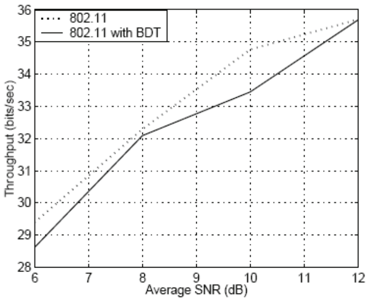

Fig. 9. Throughput of two transmission schemes: 802.11 with BDT, and plain 802.11.

5. Conclusion

We propose an opportunistic transmission strategy for wireless sensor networks that operate in a strict energy-constrained environment. The WSNs of interest in this work are assumed to host delay-sensitive applications. Our proposed transmission strategy named BDT attempts to transmit at good channel conditions while meeting the delay constraint, under time-varying wireless channel. The Markov decision process is used to find optimum thresholds for transmit action. Our BDT scheme initiates transmission only when the channel quality exceeds the optimum threshold, so that unsuccessful transmissions causing a waste of energy are avoided whenever possible. This scheme can be applied for existing MAC protocols. Extensive simulations are performed to verify the performance of our proposal over wireless fading channels. The simulation results show that the BDT scheme has 35% higher energy efficiency than its counterparts, thereby further prolonging the network lifetime.

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