DISTRIBUTED OPPORTUNISTIC TRANSMISSION FOR WIRELESS SENSOR NETWORKS

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ABSTRACT

We consider protocol design for extracting information at sensors by a mobile access point. Energy efficiency, defined as the expected number of bits reliably received for each unit of energy consumed, is used as the performance measure. A distributed opportunistic information retrieval protocol which exploits channel state information (CSI) is proposed. Referred to as the CSI-based carrier sensing, this protocol encodes the channel state into the backoff strategy of carrier sensing. When the propagation delay is negligible, CSI-based carrier sensing achieves the highest energy efficiency of the opportunistic strategy. For significant propagation delay, we construct the backoff function which maps the channel state to backoff time to minimize the performance loss. The CSI-based carrier sensing with the constructed backoff strategy is shown to be robust to propagation delay.

1. INTRODUCTION

1.1. Opportunistic Strategy

We consider the problem of information retrieval in sensor networks with mobile access points (SENMA) [1] where data at sensors are collected by a mobile access point. As illustrated in Fig. 1, sensors in the coverage area of the mobile access points transmit their measurements after being activated by a beacon signal from the mobile access point. To efficiently utilize the common wireless channel shared by all activated sensors, an information retrieval protocol has to be carefully designed to determine how many and which sensors should transmit in each time slot.

Information retrieval in SENMA can be viewed as many-to-one multiaccess communications where a classical measure of efficiency for identical nodes is the sum-rate. Assume that the flat fading channels from the sensors to the mobile access point are identically and independently distributed. Under a constrain on the average transmission power at each sensor, the ground breaking work of Knopp and Humblet [2] suggests that the information retrieval protocol for maximizing sum-rate is to enable, in each slot, only the sensor with the best channel to transmit. The idea behind this opportunistic strategy is that each sensor, with a constrained average transmission power, should save power when its channel is poor and act when opportunities arise. The optimality of this strategy is independent of the number of activated sensors. Since the quality of the best channel improves with the number of activated sensors, the sum-rate of the opportunistic strategy increases with the size of the coverage area.

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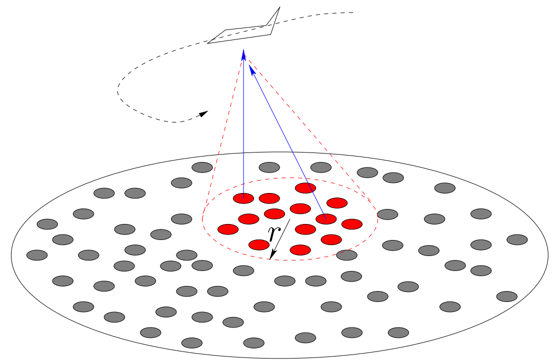

Fig. 1: Sensor networks with mobile access points.

1.2. Energy Efficiency Measured in Bits Per Joule

The optimality of the opportunistic strategy relies on the assumption that channel acquisition does not contribute to the power constraint. Approximately true in communication networks where power consumed in data transmissions dominates, this assumption needs to be reexamined for sensor networks. Channel acquisition requires, at least, each activated sensor listens to the beacon signal broadcast by the mobile access point, and listening has been recognized as an important factor in the power consumption of sensor networks [3] [1].

To fully characterize power consumed in the sensor network, we use sum-rate per unit cost as the performance measure where the cost is the power consumption. This metric can be traced back to capacity per unit cost first considered by Gallager [4] and later by Verdú [5]. In the unit of bits per Joule, it measures the energy efficiency of information retrieval protocols. Assume that each sensor transmits with a fixed power. The energy efficiency of an information retrieval protocol is the ratio of the average number of bits reliably received by the mobile access point to the total energy consumed during the transmission. For the opportunistic strategy which is optimal for sum-rate, the energy efficiency under additive white Gaussian noise can be written as

$$S = \frac{WT\mathbb{E}[\log(1+\rho\gamma^{(1)})]}{E_c + E_t} \quad \text{bits/Joule}, \tag{1}$$

where W is the bandwidth, T the slot length, ρ the expected SNR at the receiver, $\gamma^{(1)}$ the random fading gain of the best channel, E_t the transmission energy consumed in one slot, and E_c the cost of acquiring the channels of all activated sensors and selecting the sensor with the best channel. Let Λ denote the average number of activated sensors. We have

$$E_c \geq \Lambda e_c, \tag{2}$$

where e_c is the energy consumed by one sensor in estimating its channel.

When E_c is negligible as compared with E_t, the opportunistic strategy which enables the sensor with the best channel is again optimal [6]. However, the optimality of the opportunistic strategy under the metric of bits per Joule depends on the number of activated sensors. Although the sum-rate in the numerator of (1) improves with the number of activated sensors[1], this gain does not always justify the linear increase in the channel acquisition cost (see (2)). In Figure 2, we illustrate the generic characteristics [6] of the energy efficiency of the opportunistic strategy. When the expected number Λ of activated sensors is small, the gain in sum rate due to the use of better channels dominates the increase in power consumption. As Λ increases beyond certain value, the energy cost of acquiring the channel states of every activated sensors overrides the improvement in sum-rate; opportunistic strategy is inferior to a simple deterministic scheduling where all sensors use a predetermined schedule that enables n sensors in each slot for transmission[2].

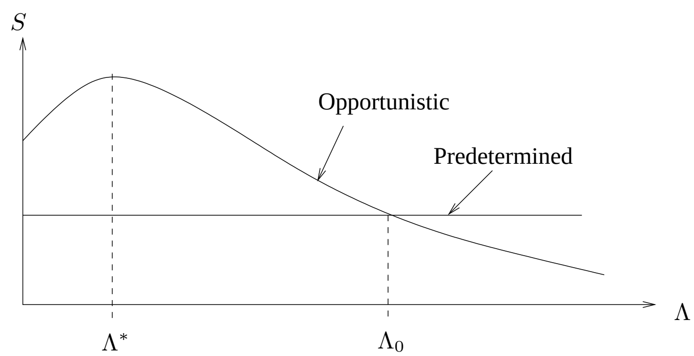

Fig. 2: Energy efficiency characteristics.

1.3. Distributed Opportunistic Transmission

To optimize the energy efficiency of the opportunistic strategy, it is critical, as shown in Figure 2, to control the average number Λ of activated sensors. In Section 4, we study possible schemes of controlling Λ and examine the optimal Λ as a function of the average received SNR ρ.

The performance of the opportunistic strategy also depends heavily on the ability of the information retrieval protocol to select efficiently the sensor with the best channel. The best performance of the opportunistic transmission occurs when E_c assumes its lower bound given in (2). This requires that sensors, each only with the knowledge of its own channel state, can determine the one with the best channel at no cost. It is also possible that sensors transmit pilot signals so that the mobile access point can estimate the channels and select the sensor with the best channel. This scheme is clearly problematic as the transmission of pilots may consume an unacceptable level of energy.

In [6], a distributed opportunistic transmission protocol is proposed which achieves the best possible energy efficiency of the opportunistic strategy. Referred to as CSI-based carrier sensing, the basic idea of this protocol is to incorporate channel state into the backoff strategy of carrier sensing: each sensor measures the channel state from the beacon of the mobile access point and generates the backoff time based on its channel. The stronger the channel, the shorter the backoff, which ensures that the sensor with the highest channel gain transmits.

In [6], the CSI-based carrier sensing is developed under the assumption of negligible propagation delay. When there is substantial propagation delay, the backoff function which maps the channel state to backoff time has to be designed judiciously to minimize the performance loss. In this paper, we construct the backoff function and demonstrate that the performance of the CSI-based carrier sensing degrades gracefully with the propagation delay.

2. THE NETWORK MODEL

2.1. The Sensor Nodes

We assume that the sensors in the network form a two-dimensional Poisson field with mean λ nodes/m^2. Suppose that with probability p, each sensor wakes up independently to detect the beacon signal of the mobile access point. Then the number M of activated sensors within the coverage area (a disk with radius r) of the mobile access point is a Poisson random variable, *i.e.,*

$$P[M = k] = \frac{e^{-\Lambda}(\Lambda)^k}{k!},$$

where the average number of activated sensors is given by

$$\Lambda = \pi r^2 \lambda p. \tag{3}$$

2.2. The Wireless Fading Channel

The physical channel between a sensor node and the mobile access point is subject to flat Rayleigh fading with a block length of T seconds. Consider slotted transmission where each slot lasts T seconds. The channel between a sensor node and the mobile access point is thus constant within each slot and varies independently from slot to slot. Without loss of generality, we consider the first slot where n nodes are transmitting simultaneously. The received signal $y(t)$ at the mobile access point can be written as

$$y(t) = \sum_{i=1}^{n} \sqrt{\gamma_i} x_i(t) + n(t), \quad 0 \le t \le T, \tag{4}$$

where $x_i(t)$ is the transmitted signal from sensor i, $n(t)$ the white Gaussian noise with power spectrum density $N_0/2$, and γ_i the channel gain between node i and the mobile access point. Assuming the channels from different sensor nodes to the mobile access point is i.i.d., we model γ_i as an exponentially distributed random variable with mean normalized to 1.

We assume each sensor transmits with a fixed output power P_{out}. The average received SNR ρ is given by

$$\rho = \frac{P_{\text{out}}}{d^\alpha N_0 W}, \tag{5}$$

where d is the distance between the sensor nodes and the mobile access point, α the attenuation coefficient, and W the transmission bandwidth.

[1]The average quality of the best channel $\gamma^{(1)}$ improves with the number of activated sensors.

[2]In the predetermined scheduling, n can be optimized using the channel distribution.

2.3. The Radio Model

At the beginning of each slot, the mobile access point broadcasts a beacon signal to activate sensors within its coverage area of radius r (see Figure 1). Activated sensors may use this beacon signal to estimate their channel state γ_i.

In each slot, energy consumed by activated sensors may come from three operations: channel state estimation, signal reception, and transmission. Let E_c denote the total cost of channel estimation in one slot. Let E_r and E_t denote, respectively, total energy consumed in receiving and transmitting in one slot. We have [3]

$$E_r = \mathbb{E}[P_{\text{rx}} \sum_{i=1}^{M} T_{\text{rx}}(i)], \quad (6)$$

$$E_t = \mathbb{E}[P_{\text{tx}} \sum_{i=1}^{M} T_{\text{tx}}(i)], \quad (7)$$

where the expectation is with respect to M, $T_{\text{rx}}(i)$ and $T_{\text{tx}}(i)$ are the average reception and transmission time of node i, P_{rx} is the sensor receiver circuitry power, P_{tx} is the power consumed in transmission which consists of transmitter circuitry power and antenna output power P_{out}.

3. CSI-BASED CARRIER SENSING

3.1. The Basic Idea

The key idea of CSI-based carrier sensing is to exploit channel state information in the backoff strategy of carrier sensing. After each activated sensor measures its channel gain γ_i using the beacon of the mobile access point, it chooses a backoff τ based on a predetermined function $f(\gamma)$ which maps the channel state to a backoff time and then listens to the channel. A sensor will transmit with its chosen backoff delay if and only if no one transmits before its backoff time expires. If $f(\gamma)$ is chosen to be a strictly decreasing function of γ as shown in Figure 3, this CSI-based carrier sensing will ensure that only the sensor with the best channel transmits. Under the assumption of negligible propagation delay, $f(\gamma)$ can be any decreasing function with range $[0, \tau_{\text{max}}]$, where τ_{max} is the maximum backoff. Since τ_{max} can be chosen as any positive number, the time required for each sensor listening to the channel can be arbitrarily short. Hence, energy consumed in each slot comes only from each sensor estimating its own channel state and the transmission from the sensor with the best channel. CSI-based carrier sensing thus achieves the best possible energy efficiency of the opportunistic strategy.

3.2. Backoff Function Design

In the case of small propagation delay, energy consumed in carrier sensing is negligible due to the arbitrarily small carrier sensing time τ_{max}. Furthermore, using any decreasing function as the backoff function $f(\gamma)$ avoids collision, an event where several nodes transmit simultaneously while no information is received at the mobile access point. When there is substantial propagation delay, however, collision and energy consumed by carrier sensing[3] are inevitable. To maintain the optimal performance achieved under negligible propagation delay, $f(\gamma)$ needs to be designed judiciously to minimize

[3]Listening to the channel requires the receiver being turned on, which consumes energy as given in (6).

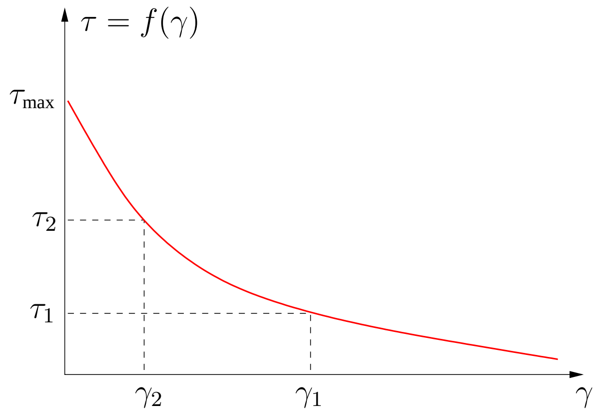

Fig. 3: CSI-based carrier sensing.

both the occurrence of collision and energy consumed in carrier sensing. Unfortunately, these are two conflicting objectives. On one hand, choosing a larger τ_{max} makes it more likely to map channel gains to well-separated backoff times, thus reducing collisions. One the other hand, a larger τ_{max} results in less transmission time and more energy consumption of carrier sensing.

To balance the tradeoff between collision and energy consumption of carrier sensing, we propose $f(\gamma)$ as illustrated in Figure 4. This backoff scheme is an even stair function on a finite interval (γ_l, γ_u). The height of each stair is the maximum propagation delay β among activated sensors, and the number of stairs is τ_{max}/β. Sensors with channel gains greater than γ_u transmit without backoff ($\tau = 0$) while sensors with channel gains smaller than γ_l turn off their radios until next slot ($\tau = T$), without even participating in the carrier sensing process.

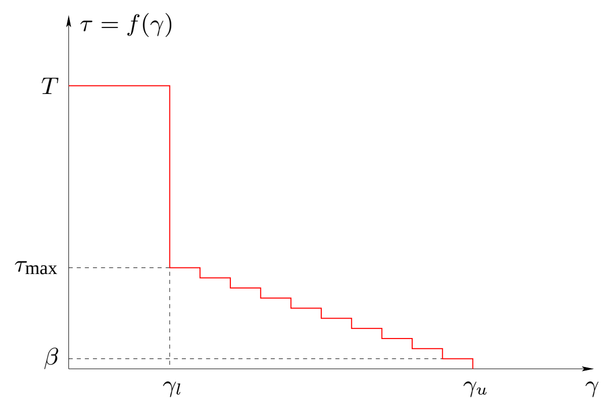

Fig. 4: Backoff function under significant propagation delay

The proposed backoff function is completely determined by γ_l, γ_u, and τ_{max}. The choice of a finite γ_u allows better resolution among highly likely channel realizations. The option of a non-zero γ_l avoids the listening cost of sensors whose channels are unlikely to be the best. For a relatively large Λ, a large percentage of activated sensors can be freed of carrier sensing cost with a carefully chosen γ_l. The maximum backoff time τ_{max} is chosen to balance collision and energy consumption of carrier sensing. It is jointly optimized with γ_l and γ_u to maximize energy efficiency:

$$\{\gamma_l, \gamma_u, \tau_{max}\} = \arg\max S(\gamma_l, \gamma_u, \tau_{max}). \quad (8)$$

The optimal $\{\gamma_l, \gamma_u, \tau_{max}\}$ can be obtained via numerical evaluation or simulations. To narrow the search range of γ_l and γ_u, asymptotic extreme order statistics can be exploited. For a relatively large Λ, the best channel gain $\gamma^{(1)}$ is of the order of $\log(\Lambda)$.

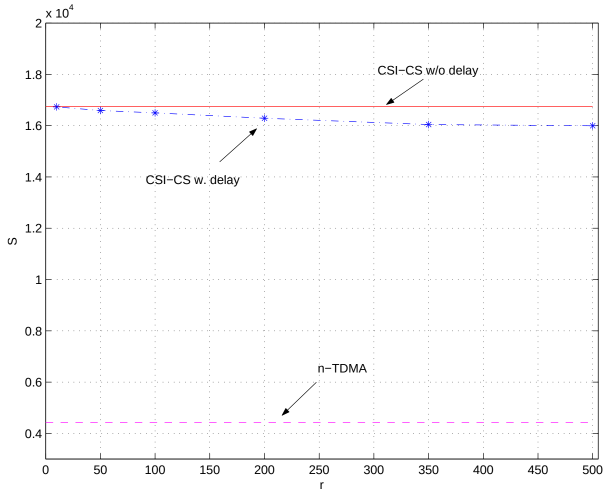

Fig. 5: Performance of CSI-based carrier sensing under significant delay ($\Lambda = 100$, $W = 1$kHz, $\rho = 3$dB, $T = 0.01$s, $P_{\text{tx}} = 0.181$w, $P_{\text{rx}} = 0.18$w, $e_c = 1.8$nw).

We now consider a simulation example to evaluate the performance of CSI-based carrier sensing with the backoff function $f(\gamma)$ given in Figure 4. We model the coverage area of the mobile access point as a disk with radius r (see Figure 1). The maximum propagation delay β is then given by $\beta = \frac{2r}{v_l}$ where v_l is the speed of light. We consider here the worst case scenario where the propagation delay among any two sensor nodes is β. Shown in Figure 5 is the energy efficiency of CSI-based carrier sensing (CSI-CS) as a function of the radius r of the coverage area which determines the maximum propagation delay. Compared with the performance in the ideal scenario (no propagation delay), the performance of CSI-based carrier sensing degrades gracefully with propagation delay. Even with a coverage radius of 500 meters, the performance degradation cost by propagation delay is less than 5%.

4. THE OPTIMAL NUMBER OF ACTIVATED SENSORS

To maximize the performance of the CSI-based carrier sensing protocol, the average number Λ of activated sensors should be carefully chosen. The average number of activated sensors can be controlled via the coverage area of the mobile access point or the duty cycle specified by p (see (3)). In Figure 6, we plot the optimal average number Λ^* of the activated sensors as a function of SNR ρ. We observe that Λ^* is a decreasing function of ρ. The reason for this is that the larger the average SNR ρ, the smaller the impact of $\gamma^{(1)}$ on the sum-rate (see (1)). Thus, the threshold beyond which the channel acquisition cost overrides the gain in sum-rate decreases with ρ, resulting in decreasing Λ^*.

5. CONCLUSIONS

In this paper, we study opportunistic transmission strategy for information retrieval in wireless sensor networks. Under the metric of

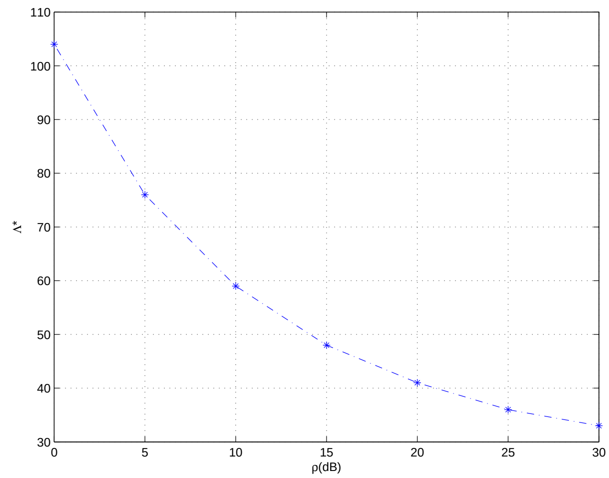

Fig. 6: The optimal number of activated sensors. ($W = 1$kHz, $T = 0.01$s, $P_{\text{tx}} = 0.181$w, $e_c = 1.8$nw).

sum-rate per unit energy cost, we show that the performance of the opportunistic strategy depends on the number of activated sensors. Possible schemes of controlling the number of activated sensors are discussed.

The basic idea of the CSI-based carrier sensing proposed in [6] is generalized to scenarios with significant propagation delay. Using asymptotic extreme order statistics, we construct the backoff function to minimize the performance loss caused by propagation delay. Simulation examples demonstrate that the performance of CSI-based carrier sensing degrades gracefully with propagation delay.

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