QoS Specific Medium Access Control for Wireless Sensor Networks with Fading

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Abstract

A new MAC protocol is proposed for the reachback operation in a wireless sensor network deployed for reconstructing a random field. Referred to as QUality-of-service specific Information REtrieval (QUIRE), the proposed protocol optimizes the network performance under the metric of information rate per slot per Joule while ensuring a given QoS requirement. Based on the density of sensor deployment and the QoS requirement specified by the maximum distortion for random field reconstruction, QUIRE partitions the sensor network into disjoint and equal-sized cells. It completely eliminates redundant transmissions by ensuring, via carrier sensing, that only one sensor in each cell transmits. It fully explores the diversity of a fading environment by incorporating channel state information into carrier sensing so that the sensor with the best channel transmits. Simulation results demonstrate that QUIRE achieves orders of magnitude of improvement in system latency and energy expenditure over fixed allocation schemes such as TDMA and random access protocols such as slotted ALOHA.

1. INTRODUCTION

1.1. Medium Access Control in Sensor Networks

In wireless sensor networks, low power and low cost sensor nodes are deployed, often in large quantities, to monitor certain phenomenon. During the reachback operation, data sensed by sensors are collected by gateway nodes where the end-user can access the data. A major issue in the reachback operation is medium access control (MAC): coordinating the transmissions from sensors to the gateway nodes to achieve efficient utilization of the common wireless channel.

MAC design for communication networks is well-studied; numerous MAC protocols - fixed allocation schemes such as TDMA and random access schemes such as ALOHA - have been proposed. Two unique features of sensor networks, however, make MAC design for sensor networks special. One is node redundancy. It is unnecessary, nor is it possible, for the mobile agent to receive every node's packet. This clearly excludes the fixed allocation schemes where every node in the network is allocated with a share of network resource (in terms of, for example, time slot, frequency bin, or orthogonal spreading code) for its exclusive use. The other feature is the regular traffic patten during the reachback operation. When the gateway nodes extracts information from the sensor network during the reachback operation, they know that every sensor node, when functioning, has a packet to transmit. This contracts sharply with conventional communication networks with random and bursty packet arrivals. Mainly designed to handle random and bursty traffic, random access protocols are incompatible with this second feature. If we allow all sensors, each holding a packet that can be strongly correlated with other sensors' data, to contend for channel access, many redundant transmissions occur, causing excessive interference and unnecessary energy expenditure.

1.2. MAC Efficiency for Sensor Networks

The goal of conventional MAC design is to achieve high throughput measured in the unit of packets per slot. For many sensor network applications, however, throughput does not represent network efficiency for the reason that packets generated

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by a sensor network can be strongly correlated. Two packets from adjacent sensors do not provide as much information as two packets from sensors far apart. Merely counting the number of packets can be misleading. Furthermore, throughput does not take into account energy consumption which is of paramount importance for sensor networks.

A good MAC protocol for the reachback operation in a sensor network should be the one that accomplishes, within the minimum amount of time using the minimum amount of energy, the task the sensor network is deployed for. Take an example where sensors are deployed to sense the radiation level around a nuclear laboratory. We say the task is accomplished if the information collected by the mobile agent is sufficient for reconstructing the radiation level in the sensed field for a given quality-of-service (QoS) requirement.

Let I denote the minimum number of packets required to reconstruct the sensed field for a given QoS, a quantity independent of MAC protocols. We measure, in the unit of information rate per slot per Joule, the performance of a MAC protocol by

$$\eta \triangleq \frac{I}{E[L\mathcal{E}]}, \tag{1}$$

where L and $\mathcal{E}$ denote, respectively, the amount of time and energy required for this protocol to accomplish the task. Besides bringing energy expenditure into the picture, this metric also correctly characterizes the amount of information provided by the collected packets. If a protocol collects more packets than necessary, those redundant packets do not contributes to the performance but rather increase the energy expenditure $\mathcal{E}$ and possibly system latency L. We point out that to measure the performance of a protocol for a given task, the quantity I is of little interests. It can be set to an arbitrary value. Without loss of generality, we set I to unity and call this performance measure η the MAC efficiency.

1.3. QoS Specific Information Retrieval

We consider MAC protocol design for SEnsor Networks with Mobile Agents (SENMA), a new network architecture proposed in [1, 2]. The novelty of SENMA is the introduction of mobile agents which are powerful nodes with the capability of traversing the sensor network, possibly with carefully designed trajectory. In contrast to the ad hoc architecture, sensors communicate directly with the mobile agents in SENMA to avoid much of the overhead associated with MAC and routing. Detailed analysis of SENMA can be found in [1, 2].

Under the network architecture of SENMA, a MAC protocol referred to as QUality-of-service specific Information REtrieval (QUIRE) is proposed in [3]. Based on the density of deployment and the QoS specified by the maximum distortion for reconstructing the random field, QUIRE partitions the sensor network into disjoint and equal-sized cells. It completely eliminates redundant transmissions by ensuring, via carrier sensing, only one sensor in each cell transmits. In [3], the performance measure used to derive QUIRE is the weighted sum of the system latency and the total number of required transmissions. The fading characteristics of the wireless channel is not taken into account in [3].

Based on the basic protocol structure proposed in [3], we develop, in this paper, the QUIRE protocol that is optimal under the metric of information rate per slot per Joule. This change of objective changes the design of the optimal transmission control scheme presented in Section 3.2.2. Furthermore, we assume a fading environment and incorporate the knowledge of channel state information (CSI) into the carrier sensing scheme. As shown in Section 3.2.1, this CSI-based carrier sensing not only eliminates redundant transmissions, but also ensures that the sensor with the best channel among its neighbors transmits. It provides a novel approach to exploiting the multi-user diversity [4] in a distributed fashion.

1.4. Related Work

Besides SENMA, two architectures have been considered for sensor networks, namely, flat ad hoc and hierarchical ad hoc. The main theme of research activities on MAC protocol design for sensor networks is based on the flat ad hoc architecture (see [5] for a recent survey). In [6], a hierarchical ad hoc architecture named LEACH is proposed. In LEACH, sensors form clusters and only the cluster heads are responsible for relaying packets to a fixed remote base station. MAC protocols are developed [7] for the transmission from sensors to cluster heads and a variation of LEACH with improved performance can be found in [8].

Perhaps [9] and [10] are the most relevant work to this paper. In [9], the authors explicitly exploit node redundancy. They develop an adaptive scheme for each sensor to determine independently whether to transmit or not so that a fixed total number of transmissions occur in each slot. The difference between [9] and our work is that QoS in [9] is defined as the total number of transmissions that should occur in each slot and an independent channel from each sensor to the remote base station seems to be assumed. In [10], an ALOHA-based random access protocol is proposed for the reachback operation in SENMA. The novelty of [10] lies in the use of channel state information characterized by the propagation channel gain. It is shown in [10] that an asymptotic throughput no smaller than the spreading gain of the system can be achieved with arbitrarily small power in each sensor if the channel state information is used for determining each sensor's transmission probability. Different from QUIRE, the protocol proposed in [10] does not address QoS issues and employ throughput as performance measure. Being a sensor-initiated random access protocol, it does not eliminate redundant transmissions.

2. PROBLEM STATEMENT

2.1. The Random Field

Consider the example we give earlier where a sensor network is deployed to monitor the radiation level in a remote area which forms a random field. Let $\mathcal{O}$ denoting the set of points in this remote area, and $S(\mathcal{O})$ the random field. We make the following assumptions on $S(\mathcal{O})$.

A1 For all $(x,y) \in \mathcal{O}$, $S(x,y)$ has common mean and variance.

$$E[S(x,y)] = \mu, \quad E[(S(x,y)-\mu)^2] = \nu^2.$$

A2 The correlation function of $S(\mathcal{O})$ is spatially homogeneous.

$$R((x,y),(u,v)) \stackrel{\Delta}{=} E[(S(x,y)-\mu)(S(u,v)-\mu)] = R(d((x,y),(u,v))),$$

where $d((x,y),(u,v)))$ is the Euclidean distance between (x,y) and (u,v).

A3 $R(d)$ is continuous and monotonically decreasing on $[0, d_{max}]$, where d_{max} is the maximum distance between two points in $\mathcal{O}$.

2.2. The Sensor Network

The distribution of sensors on $\mathcal{O}$ forms a two-dimensional Poisson field with mean λ nodes/m^2, *i.e.*, the number $N(a)$ of sensors within an area of a m^2 is a Poisson random variable with mean $a\lambda$. By the total randomness of Poisson distribution, given $N(a) = k$, these k sensors are uniformly distributed within this area of a m^2.

If a sensor locates at (x,y), it measures the value (one realization) of $S(x,y)$ and generates a packet containing its measurements to be transmitted to the mobile agent. Note that for this type of application, sensors must acquire their locations via GPS or other position estimation schemes [11–13] after deployment.

2.3. The Wireless Fading Channel

In the reachback operation, the mobile agent flies to the sensor field to collect data. Sensors start to transmit their packets according to a specific MAC protocol. We assume that the transmission time is slotted. It will become clear later that the proposed MAC protocol requires only coarse slot-synchronization among transmissions.

The physical channel between a sensor node and the mobile agent is time varying and subject to fading. Let $\gamma_i(t)$ denote the received power at the mobile agent from sensor i in slot t. Assuming slow power control is used to compensate the large scale variation, we model the fading channel as

$$\gamma_i(t) = c\phi^2, \quad \phi^2 \sim \exp(\theta), \tag{2}$$

where ϕ is a Rayleigh random variable characterizing the small scale variation in channel gain, c is a constant denoting the received power excluding small scale variation. We assume here the Rayleigh fading ϕ is i.i.d. over slots and sensor nodes. Thus, the normalized channel gain γ/c in each slot can be modeled as an exponentially distributed random variable with mean θ.

We consider a DS-CDMA system where each sensor uses a random spreading sequence with spreading gain G. We assume that a packet is successfully demodulated if the signal to interference ratio (SIR) at the receiver output is greater than a threshold β, which is a function of the modulation, error control code, and target BER. For a given receiver (for example, matched filter or linear MMSE), this SIR threshold model, together with the fading characteristics given in (2), completely specifies the channel reception capability. We point out that simultaneous reception from transmitting sensors is possible. In other words, the wireless sensor network considered here has a multiuser physical layer.

We now obtain an equivalent but more abstract channel reception model. Due to the i.i.d. distribution of the channel gain over slots and sensor nodes, we can characterize the channel reception capability by $C_{n,k}$, the probability of having k successes in a slot with n transmissions. The reception matrix of the channel is given by

$$\mathbf{C} = \begin{pmatrix} C_{1,0} & C_{1,1} & & & \\ C_{2,0} & C_{2,1} & C_{2,2} & & \\ C_{3,0} & C_{3,1} & C_{3,2} & C_{3,3} & \\ \vdots & \vdots & \vdots & \vdots & \vdots \end{pmatrix} \tag{3}$$

In general, it is difficult to obtain this reception matrix $\mathbf{C}$ analytically. However, by generating realizations of channel gain according to (2) and applying the receiver SIR threshold model, we can obtain $\mathbf{C}$ numerically.

Let

$$\mathcal{C}_n \triangleq \sum_{k=1}^{n} k C_{n,k} \tag{4}$$

be the expected number of correctly received packets when total n packets are transmitted. We then define

$$n_0 \triangleq \arg \max_{n=1,\cdots,M} \mathcal{C}_n, \tag{5}$$

i.e., when n_0 packets are transmitted simultaneously, the expected number of successfully received packets is maximized. Simultaneously enabling more than n_0 transmissions results in reduction of successful receptions and increase in energy expenditure.

2.4. QoS Requirement

After data collection, the mobile agent makes the data available to a remote control center where $S(\mathcal{O})$ is to be reconstructed. Let $\mathcal{A}$ denote all the points whose data are available to the control center. Let $\bar{\mathcal{A}}$ denote the complement of $\mathcal{A}$ in $\mathcal{O}$. Then the random field is reconstructed by approximating $S(x_0, y_0)$ for $(x_0, y_0) \in \bar{\mathcal{A}}$ using the point in $\mathcal{A}$ that is closest to (x_0, y_0)[1], *i.e.,*

$$\hat{S}(x_0, y_0) = S(x_1, y_1), \quad \text{where } (x_1, y_1) = \arg \min_{(x,y)\in\mathcal{A}} d((x_0, y_0), (x, y)). \tag{6}$$

The QoS requirement is characterized by the maximum distortion D in terms of mean square error (MSE) and the probability P_s of successful reconstruction of $S(\mathcal{O})$, *i.e.,* with a probability no smaller than P_s, every point in $\mathcal{O}$ can be estimated with an MSE no larger than D

$$E[(\hat{S}(x, y) - S(x, y))^2] \leq D \quad \forall (x, y) \in \mathcal{O}.$$

Here we assume errors caused by quantization and sensor's limited accuracy are negligible compared to the approximation error given in (6).

Our problem here is to design a MAC protocol that optimizes the network performance in terms of information rate per slot per Joule for a given QoS requirement (D, P_s).

3. QOS SPECIFIC INFORMATION RETRIEVAL

QUIRE consists of two steps. First, based on the density λ of sensor deployment, autocorrelation $R(d)$ of the random field, and the QoS requirement (D, P_s), the mobile agent partitions $\mathcal{O}$ into disjoint and equal-sized cells. In the second step, one sensor from each cell transmits according to a transmission control scheme so that the MAC efficiency η is maximized.

[1] More sophisticated reconstruction techniques can be used. Here we choose a simple method for the ease of presentation.

3.1. Partitioning $\mathcal{O}$ into cells

Consider a point (x_0, y_0) in $\mathcal{O}$. Let (x_1, y_1) be the point in $\mathcal{A}$ that is closest to (x_0, y_0). From (6), we have

$$E[(\hat{S}(x_0, y_0) - S(x_0, y_0))^2] = 2\nu^2 - 2R(d((x_0, y_0), (x_1, y_1))).$$

To ensure an MSE no larger than D, we need

$$R(d((x_0, y_0), (x_1, y_1))) \geq (2\nu^2 - D)/2.$$

Define[2]

$$r \triangleq \max(\{d : R(d) \geq (2\nu^2 - D)/2, d \in [0, d_{max}]\}). \tag{7}$$

It then follows that to estimate $S(x_0, y_0)$ with an MSE no larger than D, at least one sensor should be located at most r away from (x_0, y_0) and its packet received by the mobile agent. In another word, if the mobile agent receives a packet from the sensor located at (x, y), it can reconstruct, with an MSE no larger than D, every point in the r-radius disk centered at (x, y). It follows that if we partition $\mathcal{O}$ into r-radius disks and collect one packet from the center of each disks, the whole field $S(\mathcal{O})$ can be estimated with a maximum distortion of D. Since we can not cover an area with disjoint disks without leaving gaps, we need to consider other geometric shapes to minimize the total number of cells, hence the total number of transmissions. The best choice, as we know from cellular systems, is to cover $\mathcal{O}$ with disjoint equal-sized hexagons.

Now the question is how large each cell should be. We know each cell should be contained by a r-radius disk to ensure a distortion no larger than D. But can the radius of each hexagon be as large as r? In general, no. To have a cell size of r, we require that a sensor is located exactly at the center of each cell, which, unfortunately, is a zero-probability event for finite λ. To satisfy the QoS requirement (D, P_s), the cell size has to be smaller than r. Suppose we choose $(r - r_0)$ as the radius of each hexagon. Then all points inside a cell can be estimated with a distortion no larger than D if there locates a sensor inside the r_0-radius disk at the center of the cell (see Figure 1-left), and the QoS requirement can be satisfied if the probability that a sensor locates inside the r_0-radius disk at the center of each cell is no smaller than P_s. Let A denote the area of $\mathcal{O}$. The total number M of cells is given by

$$M = \lceil \frac{2A}{3\sqrt{3}(r - r_0)^2} \rceil.$$

We thus choose r_0 as

$$r_0 \triangleq \min\{r_0 : r_0 < r, (1 - e^{-\lambda \pi r_0^2})^M \geq P_s\}, \tag{8}$$

which follows directly from the fact that the numbers of sensors inside disjoint areas are independent for Poisson distribution. We assume that the sensor network is sufficiently dense (λ sufficiently large) so that the above defined r_0 exists. This scheme of partitioning $\mathcal{O}$ into cells is illustrated in Figure 1-right.

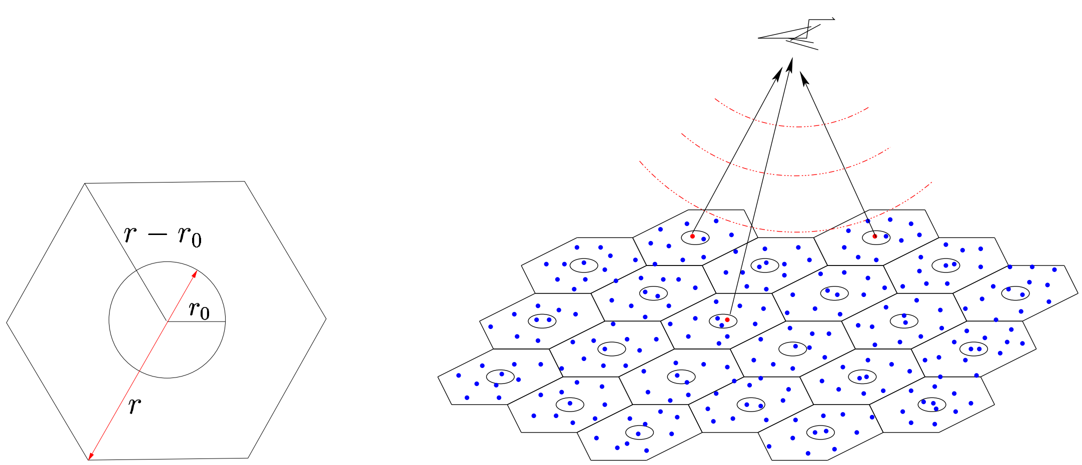

Figure 1: The cell structure of QUIRE

[2]Note that assumption A3 ensures the existence of r.

3.2. Collecting One Packet from Each Cell

The problem we have now is to design a transmission control scheme for collecting one packet from the center area of each cell, where we define center area as the r_0-radius disk at the center of each hexagon. To have a low latency, low energy cost MAC protocol, we need to eliminate redundant transmissions and fully exploit the multiuser physical layer.

3.2.1. CSI-based Carrier Sensing

Since only one packet needs to be collected from a cell, only one sensor should transmit. Without the knowledge of each sensor's location, the mobile agent can not address individual sensors for transmissions. To eliminate redundant transmissions, we propose the following scheme.

Before starting data collection, the mobile agent partitions the sensor field into cells based on r and r_0 chosen according to (7,8). To collect data from a certain cell, it broadcasts r_0 and the location of the center of this cell at the beginning of the slot. All sensors then calculate their distances to the center of this cell. If a sensor finds out that its distance to the center of the cell is larger than r_0, it refrains from transmitting. Thus, redundant transmissions from sensors outside the center area are avoided.

Now consider sensors inside the center area. To ensure that only one sensor inside the center area transmits, we use CSI-based carrier sensing. Specifically, when the mobile agent broadcasts the location of the cell center at the beginning of the slot, sensors inside the center area measure their channel gain γ using the broadcast signal. Based on this channel state information (CSI), each sensor inside the center area chooses a delay τ according to a predetermined function $f(\gamma)$ and listens to the channel. A sensor will transmit with its chosen delay if and only if no one transmits before it. Considering the relatively small size of the center area, we assume that the signal propagation delay within the center area of a cell is negligible so that carrier sensing ensures one and only one sensor from the center area transmits. Furthermore, if $f(\gamma)$ is chosen to be a strictly decreasing function, this CSI-based carrier sensing not only eliminates redundant transmissions, but also ensures that the sensor with the best channel in the center area transmits[3]. Here we assume that the channel gain from the the sensor to the mobile agent is the same as the one from the mobile agent to the sensor and remains constant within one slot.

We now characterize the reception capability of the physical layer when CSI-based carrier sensing is employed. The normalized channel γ/c between the mobile agent and sensor node is exponentially distributed with mean θ as given in (2). Due to the CSI-based carrier sensing, however, the channel gain seen by the mobile agent obeys a different distribution. Let $\check{\gamma}$ denote the normalized channel gain from a transmitting sensor to the mobile agent. It is shown in [14] that $\check{\gamma}$ has the following distribution.

$$F_{\check{\gamma}}(x) \triangleq P[\check{\gamma} \le x] = \frac{1}{1-e^{-\lambda_0}}(e^{-\lambda_0 e^{-\frac{x}{\theta}}} - e^{-\lambda_0}). \tag{9}$$

By generating realizations of $\check{\gamma}$ according to (9) and applying the receiver SIR threshold model, we can easily obtain the channel reception matrix $\mathbf{C}$ for QUIRE. In [14], numerical examples are given to demonstrate the impact of CSI-based carrier sensing on the channel reception capability.

3.2.2. Maximization of Information Rate Per Slot Per Joule

In this section, we develop the transmission control scheme for the mobile agent to collect one packet from each cell. The goal here is to fully utilize the channel reception capability given by $\mathbf{C}$ and achieve high MAC efficiency η in terms of information rate per slot per Joule.

After partitioning $\mathcal{O}$ into M cells, the mobile agent queues up all M cells and enables in each slot N cells from the head of the queue. Specifically, at the beginning of a slot, the mobile agent broadcasts the center locations of the first N cells in the queue. At the end of this slot, the mobile agent detects whether this slot is empty or not. An empty slot implies that no sensor is located in the center areas of these N cells [4]. These N cells are thus removed from the queue. On the other hand, if this slot is not empty and k $(k \ge 0)$ packets are successfully received, those k cells from which a packet is received are labeled processed and removed from the waiting queue. This procedure continues until the queue becomes empty (all M cells are processed). Here we assume that the mobile agent can distinguish between empty and nonempty slots. However, if at least one packet is successfully demodulated at the end of a slot, the mobile agent does not assume the knowledge whether there are other packets transmitted in this slot but not successfully received.

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[3] Assuming zero propagation delay within the center area of a cell, $f(\gamma)$ can be any decreasing function with range $[0, \tau_{max}]$, where τ_{max} can be any positive number. For significant propagation delay, $f(\gamma)$ needs to be chosen judiciously to ensure the efficiency of the CSI-based carrier sensing. This issue will be addressed in our future work.

[4] The probability of having one or more empty center areas is bounded below $1 - P_s$. See (8).

With this queue structure of the transmission control scheme, the only parameter to be designed is N, the number of simultaneously enabled cells. The optimal N^* should be chosen by maximizing the MAC efficiency $\eta \triangleq 1/E[L\mathcal{E}]$, or equivalently, minimizing $E[L\mathcal{E}]$, where L and $\mathcal{E}$ denote, respectively, the total number of slots and energy required for processing all M cells. We have,

$$N^* = \arg \min_{N=1,\cdots,N_{max}} E[L\mathcal{E} \mid N], \tag{10}$$

where $E[L\mathcal{E} \mid N]$ denotes the expected value of $L\mathcal{E}$ when the number of simultaneously enabled cells is set to N, N_{max} is the maximum number of simultaneously enabled cells to be considered. For typical applications, N_{max} can be set to n_0 defined in (5).

In order to determine N^*, we calculate $E[L\mathcal{E} \mid N]$ for $N = 1, \cdots, N_{max}$. As detailed in [14], $E[L\mathcal{E} \mid N]$ can be obtained by constructing discrete time Markov chains and analyzing their absorbing time. We point out that the calculation of N^* can be carried out off-line. Little computation is required at the mobile agent during data collection.

4. SIMULATION EXAMPLES

In this section, we present simulation examples to demonstrate the performance of QUIRE. We assume that the random field is a 200m $\times$ 200m square. The correlation function $R(d)$ of the random field and the maximum distortion D are such that r as defined in (7) is 10m. The required probability of reconstructing the random field with a maximum distortion D is given by $Ps = 0.9$.

The wireless fading channel is given in (2) where ϕ^2 is exponentially distributed with mean 1 and the constant c is given by $\frac{c}{\sigma^2} = 5dB$. The spreading gain G and the SIR threshold β for successful reception are, respectively, 16 and $3dB$. A linear MMSE receiver is used at the mobile agent. We assume here transmitting one packet costs $1.8mJ$ energy.

In Figure 2, we compare the performance of QUIRE, modified TDMA, and slotted ALOHA with optimal transmission probability under the metric of information rate per slot per Joule. The modified TDMA is built upon the cell structure and the CSI-based carrier sensing scheme of QUIRE, *i.e.*, cells are enabled one by one in each slot and only the sensor with the best channel in the center area transmits. For slotted ALOHA, it is implemented as follows. At the beginning of data collection, the mobile agent, based on the total number of sensors in the field, chooses the optimal transmission probability P_t by maximizing the expected number of successful receptions. It than broadcast P_t and all sensors flip a coin with bias P_t to determine whether to transmit in this slot. At the end of this slot, the mobile agent broadcast the location of all sensors whose packets are successfully received in this slot. All sensors within r distance of these successful sensors will go to sleep; they will not transmit in the future slots of this data collection. At the beginning of the second slot, the mobile agent, assuming the total number of active sensors (excluding all those within r distance of successful sensors), chooses and broadcasts the optimal transmission probability P_t for this slot. This procedure continues until the whole network is covered (the number of active sensors becomes 0). Note that we intentionally favor slotted ALOHA by assuming the knowledge of active sensors in each slot, while QUIRE only assumes the network density λ.

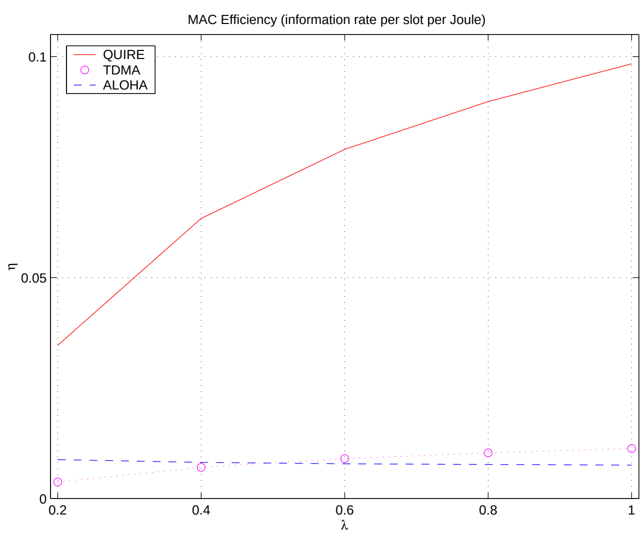

Figure 2: Comparison of MAC efficiency.

Figure 2 demonstrates the Superior performance of QUIRE. The MAC efficiency η is 10 times higher for QUIRE at $\lambda = 1$ as compared to modified TDMA and slotted ALOHA with optimal transmission probability. The improvement over modified TDMA, which is built upon the cell structure and CSI-based carrier sensing scheme of QUIRE, is due to QUIRE's optimal exploitation of the multiuser physical layer. The improvement over slotted ALOHA results from a combination of QUIRE's capability of eliminating redundant transmissions and fully utilizing the improved channel reception capability.

5. CONCLUSION

In this paper, we consider MAC protocol design for large scale, densely deployed sensor networks. We explicitly incorporate the QoS issue into medium access control. A new performance measure - MAC efficiency η in the metric of information rate per slot per Joule - is introduced that correctly characterizes the amount of information provided by the collected packets and takes energy consumption into consideration. Under this performance measure, we propose QUIRE, a MAC protocol that assures QoS requirement while maximizing MAC efficiency. It completely eliminates redundant transmissions by partitioning the sensor field into disjoint and equal-sized cells. With CSI-based carrier sensing and a transmission control scheme which chooses the optimal number of simultaneously enabled cells, QUIRE fully exploits the wireless multi-user physical layer in a fading environment. The CSI-based carrier sensing scheme proposed in this paper opens new possibilities for utilizing the channel state information. Coupled with carrier sensing, the utilization of CSI exploits the fading environment in an optimal way.

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