OPPORTUNISTIC ALOHA AND CROSS LAYER DESIGN FOR SENSOR NETWORKS

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ABSTRACT

We propose a novel distributed medium access control scheme called opportunistic ALOHA for reachback in sensor networks with mobile agents. Each sensor transmits its information with a probability that is a function of its channel state (propagation channel gain). This function called transmission control is then designed under the assumption that orthogonal CDMA is employed to transmit information. The gains achieved in the throughput by use of transmission control are analyzed and evaluated numerically. The variation of the average number of transmitting users with distance from the collecting agent is analyzed. The proposed reachback protocol can be used in a variety of sensor network applications. We end by giving two examples of how the reachback protocol can be used by the sensor network to transmit information reliably to the collecting agent. The maximum rate at which the information can be reliably transmitted with the proposed schemes is evaluated as a function of the performance parameters of the reachback protocol.

1. INTRODUCTION

We consider the design of random access for sensor network with mobile agents (SENMA) [8]. As an architecture illustrated in Fig. 1, SENMA has two types nodes: a large number of low power sensors and a few mobile agents that are for retrieving data from the sensor network.

The design of random access protocol for SENMA is nontrivial. The large number of sensor nodes, the lack of central control, the channel fading and node duty cycle all make the design of medium access control (MAC) especially challenging. For such a network, it is desirable that the MAC protocol has the following properties:

- The MAC should be distributed and easy to implement. Each node should involve minimum calculation and rely as little as possible on feedback.
- The MAC should have high throughput and high efficiency in channel utilization. While the data rate from each sensor node is very low, the time allowed for the mobile agent to collect data can be severely constraint, especially in some military applications. This means that the mobile agent should collect as many packets as possible in each slot.
- The MAC must be power efficient. For large scale sensor networks, the battery operated sensor has limited power and can only reach the mobile agent under special fading conditions. It is therefore necessary that the sensor transmits only when favorable opportunities arise.

In this paper, we consider an approach based on the principle of cross layer design that integrates physical layer characteristics with medium access control. In particular, we proposal Opportunistic ALOHA (O-ALOHA) as the medium access control for SENMA.

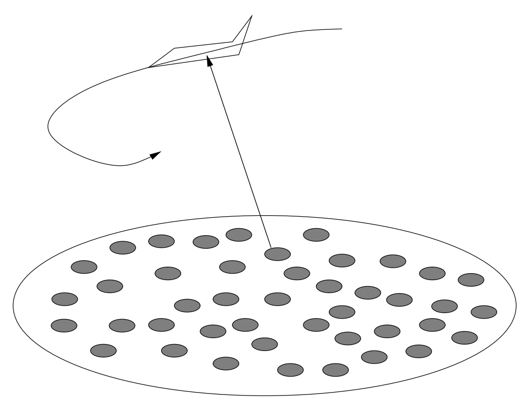

Fig. 1: Sensor Network with Mobile Agent

A similar protocol was introduced and analyzed for the collision channel model by Qin and Berry in [9]. The O-ALOHA protocol was then investigated by Adireddy and Tong in the context of more sophisticated reception models and large number of users in [2, 1]. It was shown in [2, 1] that the effect of using O-ALOHA is equivalent to changing the underlying probability distribution of the channel state. We developed a frame work for transmission control which asymptotically (in the number of users) enables one to manipulate the existing channel state probability distribution to a large class of distributions. The choice of the specific target probability distribution and therefore the specific transmission control however depends on the physical layer of the sensor network. In this paper, we design the O-ALOHA

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protocol in the context of a direct sequence spread spectrum network. We propose transmission controls that demonstrate good performance in terms of throughput. Through simulations, we study other important properties of the O-ALOHA protocol like the pattern of transmitting users. We also give two examples of how the O-ALOHA protocol can be utilized to transmit data reliably to the collecting agent.

The idea of using centralized channel state information in multiple access was first considered by Knopp and Humblet [7], Tse and Hanly [4] and others, all in the information theoretic setting. The main conclusion is twofold. First, it is desirable to schedule the transmission based on users' channel states. Second, when the number of users is large, the effect of multiuser diversity significantly improves the throughput. The distributed use of channel state information was considered by Telatar and Shamai [5] and Viswanath, Tse and Anantharam [6], again using the information theoretic metric. They concluded that the loss of using distributed use of channel state incurs little loss comparing with schemes using centralized scheduling. Qin and Berry [9] proposed "channel aware" ALOHA that incorporates channel state in ALOHA. Using a simple threshold policy under the collision model, they demonstrate the effect of multiuser diversity. The threshold policy, however, is in general not optimal. The major difference between their approach and the one considered in this paper (also in Adireddy and Tong [1]) is that our scheme is optimized over a general class of transmission control. Our reception model that takes into account multipacket reception is also more general.

The rest of the paper is organized as follows. In Section 2, we describe the reachback protocol and the system model. In Section 3, we introduce the transmission control and in Section 4 we illustrate the properties of the transmission control. In Section 5, we show how the reachback protocol can be used to deliver data and in Section 6 we list our conclusions.

2. REACHBACK PROTOCOL

2.1. Protocol Discipline

In this section, we describe the working of the O-ALOHA protocol. We consider a network where n sensors communicate with a mobile agent over a common channel. During the time period that the mobile agent is in the vicinity of the network, we assume that every sensor has data to transmit. Time is slotted into intervals of equal length that is equal to the time required to transmit a packet. We make the slot time equal to one time unit and slot t is assumed to occupy the time $[t, t+1)$. The slot structure is as shown in Fig. 2. The network is assumed to operate in time division duplex (TDD) mode. At the beginning of each slot, the collection agent transmits a beacon. The beacon is used by each sensor to estimate the propagation channel gain from the collection agent to itself. Due to reciprocity, this is same as the channel from the sensor to the collection agent. We denote $\gamma_i^{(t)}$ as the channel from sensor i to the collection agent during slot t. For simplicity, we assume that the channel estimation is perfect. During the data transmission period, each sensor transmits its information with a probability $s(\gamma_i^{(t)})$ where $s(\cdot)$ is a function that maps the channel state to a probability. The protocol mandates that the probability of transmission is a function of channel state. Hence it is called opportunistic ALOHA (O-ALOHA).

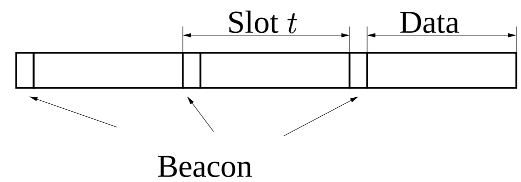

Fig. 2: Slot Structure

2.2. Channel Model

In this section, we describe the channel model that is used for analyzing the O-ALOHA protocol. We assume that the all the sensors are located in a disc of radius 1. As shown in Fig. 3, the collection agent is assumed to be a distance d above the center of the disc. Let r_i be the radial distance of sensor i. We model r_i as a random variable that is uniformly distributed between 0 and 1. The propagation channel gain between sensor i and the base station is modeled as

$$\gamma_i^{(t)} = \frac{P_T R_{it}^2}{r_i^2 + d^2}, \tag{1}$$

where R_{it} is Rayleigh distributed. In addition, assume that R_{it} is independent and identically distributed between slots and sensors. The transmission power of each sensor P_T is included in $\gamma_i^{(t)}$ in order to simplify the notation. We denote $f(\gamma)$ as the probability density function (pdf) of $\gamma_i^{(t)}$. Due to the assumptions made, note that the probability density function does not depend on i (sensor) or t (slot). We also use $f(\gamma|r)$ to denote the probability density function of the channel state of a sensor conditioned on the event that its radial distance is equal to r.

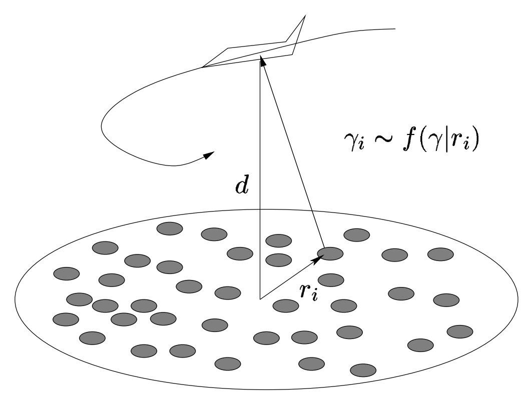

Fig. 3: Sensor Deployment

2.3. Data Transmission and Reception

We assume that the physical layer of the sensor network is a based on direct sequence spread spectrum codes. The spreading gain of the network in denoted as N. It is assumed that there is a pool of N orthogonal codes (the pair wise cross correlation is equal to zero) and each transmitting sensor selects one of the codes at random to transmit its data using the spreading code. The receiver at the collection agent performs matched filtering on each of those codes in order to demodulate the received data. It is assumed that if after matched filtering, the signal to interference ratio is greater than the threshold β then the packet is received successfully. In slot t, if K_j sensors transmit using the j^{th} spreading code and their channel states are given by $(\gamma_{j_1}^{(t)}, \cdots, \gamma_{j_{K_j}}^{(t)})$, then the criterion for successful reception of sensor i is well-approximated [3] by

$$\frac{\gamma_{j_i}^{(t)}}{\sigma^2 + \sum_{k=1, k\neq i}^{K_j} \gamma_{j_k}^{(t)}} > \beta, \tag{2}$$

where σ^2 is the variance of the background noise.

3. TRANSMISSION CONTROL

In this section, we propose different transmission controls that demonstrate good performance for the physical layer under consideration. The effect of transmission control is two fold. It can be used to regulate interference by controlling the average number of transmitting sensors. Also, when the transmission control can depend on the channel state, it can also be used to change the aposteriori channel state distribution (distribution of channel state conditioned on the event that a sensor transmitted) [2, 1].

If $f(\gamma)$ is the apriori probability density function of the channel state and $g(\gamma)$ is the target probability density function of the channel state, a transmission control that can be used to asymptotically (in the number of users) change the channel state distribution to $g(\gamma)$ is [2, 1] :

$$s_n(\gamma) = \min\left(\frac{g(\gamma)}{f(\gamma)}\frac{x}{n}, 1\right), \tag{3}$$

where n is the size of the network and x (a design parameter) is the average number of transmissions in a slot. For the PHY layer under consideration, it was shown that good target pdf are distributions with a *roll-off*. Any pdf that is of the form

$$g(\gamma) = \frac{\delta}{\gamma_0^{-\delta} - \gamma_1^{-\delta}} \frac{1}{\gamma^{1+\delta}} 1_{[\gamma_0 \leq \gamma \leq \gamma_1]} \tag{4}$$

where $0 < \delta < 1$ is considered to a density function with a roll-off. The parameters of the density function are δ, γ_0 and γ_1. It is important to choose all of them judiciously for good performance.

3.1. Location Independent Transmission Control (LIT)

Location independent transmission control (LIT) refers to the case when the decision to transmit a packet is made by observing γ alone. Motivated by the discussion in the previous section, LIT is derived from prior and target distributions as

$$s_n(\gamma) = \min\left(\frac{g(\gamma)}{f(\gamma)}\frac{x}{n}, 1\right), \tag{5}$$

where $g(\gamma)$ is the density of the target distribution, and the density $f(\gamma)$ is the (prior) pdf of the channel state. Since $f(\gamma)$ can be calculated before deployment, the sensor transmission control can be completely designed prior to deployment. It is therefore simple to implement.

3.2. Location Aware Transmission Control (LAT)

In Location Aware Transmission Control (LAT), every sensor makes an estimate of its radial distance and the decision to transmit is a function of both the channel state γ and the location of the sensor r. The transmission control $s_n(\gamma, r)$ is chosen as

$$s_n(\gamma, r) = \min\left(\frac{g(\gamma)}{f(\gamma|r)}\frac{x}{n}, 1\right), \tag{6}$$

where $f(\gamma|r)$ is the pdf of the channel state conditioned on the distance of the sensor. LAT is conceivably harder to implement that LIT because each sensor is needed to make an estimate of its location. But, as we see in the next section the properties of LAT might some times justify the additional complexity. Note that LAT can be interpreted as the transmission control derived by assuming that $(\gamma_i^{(t)}, r_i)$ is interpreted as the channel state of sensor i. The apriori CSI distribution is then equal to $t(r)f(\gamma|r)$, where $t(r)$ is the distribution of the radial distance. The target distribution of the CSI is chosen as $t(r)g(\gamma)$.

4. PROPERTIES OF TRANSMISSION CONTROL

In this section, we investigate the properties of the proposed transmission controls through simulations. The parameters of the simulations are chosen as follows. The height of the collecting agent is selected as $d = 4$. The spreading gain of the network is chosen as $N = 16$. The transmit SNR of each sensor $\frac{P_T}{\sigma^2}$ is chosen as 6 dB. The threshold for demodulation β is selected to be 4 dB. The roll-off δ of the target distribution is chosen as 0.5. The parameter γ_0 is chosen as 1.5 and γ_1 is chosen as 14.

4.1. Throughput

The expression for the throughput of a sensor network with n nodes $T(n, s_n(\cdot))$ is given by [2, 1]

$$T(n, s_n(\cdot)) = \sum_{j=1}^{N}\sum_{i=1}^{n}\binom{n}{k}(1-q_j p_{s_n})^{n-k}(q_j p_{s_n})^k C_k(G_{s_n}(\cdot)), \tag{7}$$

where p_{s_n} is the probability of transmission,q_j is the probability of choosing the j^{th} spreading code, $G_{s_n}(\cdot)$ is the aposteriori CSI distribution and $C_k(\cdot)$ is the average number of packets received successfully when k nodes transmit and their channel states are drawn i.i.d according to $G_{s_n}(\cdot)$. For LIT, we have

$$p_{s_n} = \int s_n(\gamma)f(\gamma)d\gamma, \tag{8}$$

where as for LAT we have

$$p_{s_n} = \int s_n(\gamma, r)f(\gamma|r)t(r)d\gamma dr, \tag{9}$$

where $t(r)$ is the pdf of the radial distance of a sensor. For LIT the aposteriori CSI distribution is given by

$$G_{s_n}(\gamma) = \frac{1}{p_{s_n}} \int_0^{\gamma} s_n(y) f(y) dy, \tag{10}$$

and for LAT the aposteriori CSI distribution is given by

$$G_{s_n}(\gamma) = \frac{1}{p_{s_n}} \int_0^{\gamma} \int_0^{1} s_n(y,r) f(y|r) t(r) dr dy. \tag{11}$$

In [1], we have shown that if $nq_j p_{s_n} \to x$ and $G_{s_n}(\gamma)$ converges point wise to $G(\gamma)$, then

$$T(n, s_n(\cdot), j) \to \sum_{k=1}^{\infty} \frac{e^{-x} x^k}{k!} C_k(G(\cdot)) \triangleq \eta(x, j). \tag{12}$$

where $T(n, s_n(\cdot), j)$ refers to the throughput using the j^{th} spreading code. Fig. 4 and Fig. 5 illustrate the throughputs obtained by the use of transmission control. They show the variation of throughput of the LIT and LAT protocols with x, the average number of transmissions (design parameter) and n, the size of the network. The figures also show the gains of O-ALOHA over a simple TDMA scheme, where every slot, N particular sensors are scheduled to transmit irrespective of their channel states using the N orthogonal spreading codes. It can be seen from the plots that the throughput of TDMA schemes decreases towards zero with reduction in transmitted power. However, in the O-ALOHA transmission scheme, the throughput converges to the theoretical curve with increase in size of network irrespective of transmitted power. Thus, the O-ALOHA transmission scheme has a clear advantage over the TDMA scheme. Further, the gains obtained using LIT and LAT are almost identical.

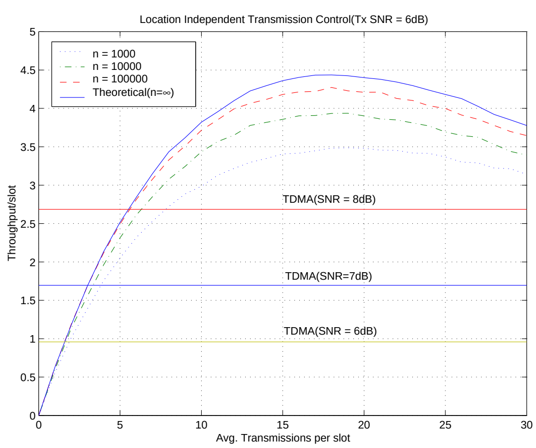

Fig. 4: Performance of LIT

4.2. Transmission Pattern

LIT is a MAC protocol that is simpler to implement than LAT but we found in the previous section that both these protocols have identical performance in terms of overall throughput. The difference between LIT and LAT is primarily is primarily how the number of transmitting sensors and successful sensors variation with

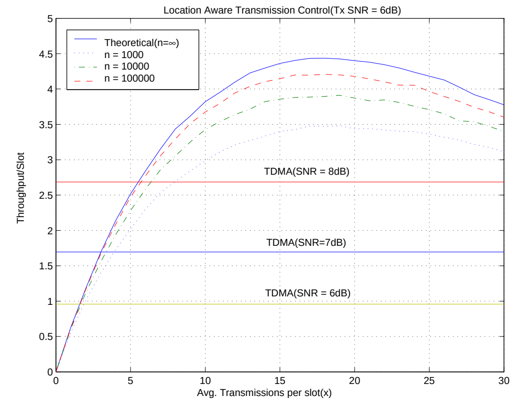

Fig. 5: Performance of LAT

the distance from the collecting agent. If the network employs LAT, the probability of transmission for sensor i, conditioned on the event that $r_i = r$ is given by

$$\Pr\{\text{Tx}|r_i = r\} = \int s_n(\gamma, r) f(\gamma|r) d\gamma. \tag{13}$$

It is easy to show that for LAT

$$n\Pr\{\text{Tx}|r_i = r\} \to x \tag{14}$$

and therefore the probability of transmission is independent of the distance from the collecting agent. However, for LIT we have

$$\Pr\{\text{Tx}|r_i = r\} = \int s_n(\gamma) f(\gamma|r) d\gamma. \tag{15}$$

and

$$n\Pr\{\text{Tx}|r_i = r\} \to x \int \frac{g(\gamma) f(\gamma|r)}{f(\gamma)} d\gamma, \tag{16}$$

which depends on the radial distance. As expected, Fig. 6 shows that for the LIT protocol most of the transmitting sensors are concentrated near the origin *i.e.*, they are closer to the collecting agent. But, for the LAT protocol the probability of transmission of a sensor is independent of the distance from the collecting agent.

5. CODED RANDOM ACCESS

Consider an application where the sensor network is employed to cooperate and transmit data reliably to the collection agent. In this section, we illustrate how the O-ALOHA reachback protocol can be for this application. For the method proposed, we characterize R, the number of bits per slot that can be reliably transmitted by the sensor network. We propose two coding schemes based on the dependence on the spreading code.

5.1. Spreading Code Independent Transmission

To briefly recapitulate the O-ALOHA reachback protocol, each sensor estimates its channel state information from the beacon sent by the coolecting agent, decides to transmit with probability

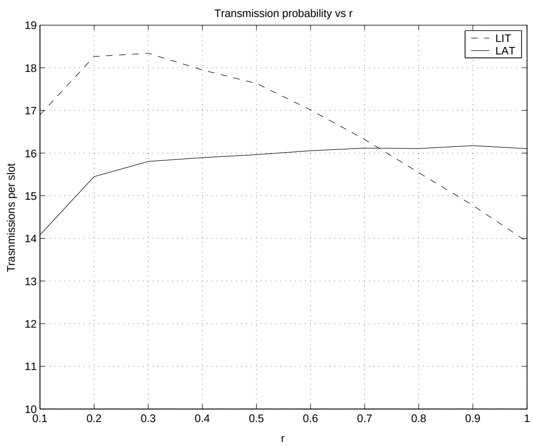

Fig. 6: Transmission Pattern

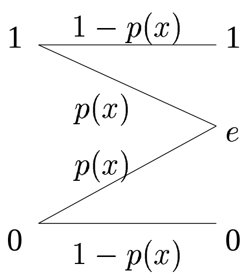

Fig. 7: Erasure Channel Model

depending on the transmission control given by $s_n(\gamma)$. Once the decision to transmit has been made, the sensor randomly picks one out of the N orthogonal spreading codes, and uses the code to transmit its data. We assume that the packets transmitted by the sensors have the following structure. The sensor network is assumed to employ a binary codebook of size $\lceil 2^{MR} \rceil \times M$, where M is the codeword length. If the sensor network decides to transmit message k in the codebook to the collecting agent the encoding is performed across time as follows. In the i^{th} slot, the collecting agent requests the transmission of the $i^t h$ bit through its beacon. All the transmitting sensors transmit the i^{th} bit of codeword k. Therefore, M slots are required for transmission of one codeword. We assume that the packets received successfully(depending on the SINR threshold) are decoded without error. Therefore the probability of erasure of a bit in the codeword is the probability that no packet was received successfully in a slot. If the average throughput per slot is assumed to be $T(x)$, then the channel between the sensor network and the collecting agent can be viewed as an erasure channel with erasure probability

$$p(x) = \left(1 - \frac{T(x)}{N}\right)^N \tag{17}$$

Since we have assumed that the SINR threshold $\beta > 1$, $\frac{T(x)}{N}$ is the probability of capture from a particular spreading code[3]. Therefore, the expression in (17) represents the probability that no packet was received from any of the N spreading codes. In order to make any statements about acheivable rates for such a system, the transmission of each bit has to necessarily be $i.i.d.$ We know that the channel state for each sensor is $i.i.d$ across slots. Since the transmission control is dependent only on the channel state, the probability of transmission in each slot is also $i.i.d.$ In this scheme, it is assumed that exactly one bit is transmitted every slot. Hence, it is clear that the transmission of each bit is $i.i.d.$ Therefore the achievable rate of such a channel is given by

$$R = 1 - \left(1 - \frac{T(x)}{N}\right)^N \text{ bits/slot} \tag{18}$$

5.2. Spreading Code Dependent Transmission

In the previous coding scheme, it is evident that by transmitting only one bit per slot, the orthogonality of the spreading codes is not being utilised. In this section we propose a modified scheme which utilises the fact that transmissions using different orthogonal codes are independent. Assume the same structure of the codebook as mentioned in the previous section. In this case, each codeword is divided into blocks of N bits, where N is the spreading gain. Therefore each codeword can be thought of as a two dimensional array $M \times N$, where M is the number of blocks and N is the number of bits per block. The codebook size is therefore $\lceil 2^{MNR} \rceil \times MN$. The spreading codes used to transmit are ordered from 1 to N. If the k^{th} message in the codebook is to be sent to the collecting agent, then the encoding is as follows. In the i^{th} slot, the collecting agent sends a request for the i^{th} block through its beacon. Every sensor that decides to transmit using spreading code j, transmits the (i, j) bit of the k^{th} codeword. In every slot, one block of the codeword is transmitted. Therefore, the number of slots required to transmit a codeword is M, the number of blocks in a codeword. This scheme has a clear advantage over the previous scheme in the sense that depending on the parameters of the transmission control, the number of bits received per slot could be more than one.

We again assume that the packets received successfully are decoded without error. Therefore the probability of erasure of a bit in a codeword is the probability that a packet was not received successfully using a particular spreading code. If we assume the probability of choosing a spreading code q_i is the same for all N spreading codes, then the probability of erasure is identical for each bit in the codeword. Since each bit transmitted in a slot is transmitted using a different orthogonal code, they do not interfere with each other and are hence independent. The transmission of a bit in a slot, is independent and identical to the transmission of a bit in another slot because of the $i.i.d$ nature of channel state distribution. Therefore, the transmission of bits using this scheme is $i.i.d.$ Hence, we can write the probability of erasure of a bit as

$$p(x) = 1 - \frac{T(x)}{N} \tag{19}$$

where $T(x)$ is the throughput per slot. $\frac{T(x)}{N}$, or the throughput per spreading code is the probability that a packet is received successfully using a particular spreading code. This is because we have assumed that the SINR threshold $\beta > 1$. Therefore, at most one packet can be received correctly per spreading code and the throughput per code is the probability of correct reception[3]. We have already shown the $i.i.d$ nature of transmission, therefore the achievable rate for this scheme is

$$R = \frac{T(x)}{N} \text{ bits/channel use} \tag{20}$$

According to this scheme, we have N channel uses per slot since the codes are orthogonal. Therefore we can write the capacity in terms of bits/slot as

$$R' = NR = T(x) \text{ bits/slot} \tag{21}$$

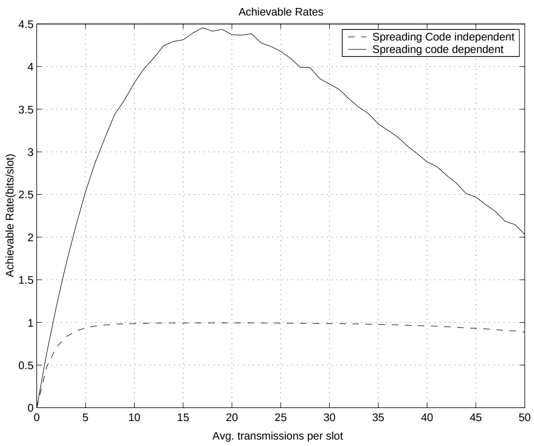

Fig. 8: Acheivable Rates

The variation in achievable rates with parameter x, the average number of transmissions per slot is shown in figure 8. It is very clear from the figure that Spreading code dependent transmission can acheive better gains in terms of bits/slot. However, for low rate codebooks, the spreading code independent scheme can be shown to have a greater error exponent than the spreading code dependent scheme.

6. CONCLUSIONS

In this paper, we introduced a reachback protocol called opportunistic ALOHA (O-ALOHA) for sensor networks with mobile agents. In this protocol, each sensor transmits its packet with a probability that is a function of the channel state. Under the assumption the sensors employ spread spectrum signaling and the receiver employs matched filtering, we proposed two types of transmission control namely Location Independent Transmission Control (LIT) and Location Aware Transmission Control (LAT). It was shown through simulation that it is possible to obtain significant gains using both LIT and LAT. The patterns of transmitting and successful sensors of both LIT and LAT were analyzed. It was found that the transmissions and successes in LIT are localized towards the collection agent where as those of LAT are independent of the distance from the collection agent. We described two schemes that employ the reachback protocol to transmit data reliably to the collecting agent. For each of the scheme, we characterized the maximum rate at which data can be transmitted to the collecting agent. [1]

[1]The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Laboratory or the U. S. Government.

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