Using Frequency Division to Reduce MAI in DS-CDMA Wireless Sensor Networks

Bao Hua Liu, Chun Tung Chou, Justin Lipman, Sanjay Jha

School of Computer Science and Engineering, The University of New South Wales
Email: {mliu, ctchou, justinl, sjha}@cse.unsw.edu.au

***Abstract*— The performance of Direct Sequence Code Division Multiple Access (DS-CDMA) sensor networks is limited by Multiple Access Interference (MAI). This paper proposes using frequency division to reduce the MAI in a DS-CDMA sensor network. We provide theoretical characterization of the mean MAI at a given node and show that a small number of frequency channels can reduce the MAI significantly. In addition, we provide a comparison of our proposed system to systems which do not use frequency division or which employ contention based protocols. Our study found that, by using only a small number of frequency channels, our system has less channel contention, lower packet latency, higher packet delivery ratio and lower energy consumption.**

I. INTRODUCTION

We consider a wireless sensor network that consists of numerous sensor/actuator devices with integrated sensing, embedded microprocessors, low-power communication radios, on-board energy, with location awareness and organized in an ad hoc multi-hop network. Since sensor network applications are expected to utilize low data rate (e.g., 1-100Kbps), have small data packet size (e.g., 50 bytes), and sensors normally have limited energy, buffer space, and other resources, the contention based protocols may not be a suitable choice.

Contention based protocols suffer from both low network throughput and long packet delays. Associating with each small data packet transmission, the RTS/CTS control packet exchange produces significant overheads. Woo and Culler [6] state that an RTS-CTS-DATA-ACK handshake sequence in transmitting a packet can constitute up to 40% overhead with small packet size in sensor networks. Although IEEE 802.11 standard specifies that RTS/CTS can be avoided with small data packet transmission, this may not be a suitable choice for sensor networks. Given the low data rate (e.g., 20Kbps) in sensor networks, a *small* data packet will take longer time to transmit than in an IEEE 802.11 network which has higher data rate (e.g., 2Mbps). As a result, the collision probability in sensor networks is much higher. Moreover, some energy efficient algorithms proposed for contention based protocols for sensor network require the information embedded in RTS/CTS packets. For example, SMAC [7] uses the transmission time embedded in RTS/CTS to turn off unintended receivers to avoid the energy consumption caused by overhearing. Furthermore, contention based protocols also suffer from the well documented hidden node and exposed node problems.

It is well known that energy consumption is the crucial factor in sensor network design. This may lead to sensor network MAC protocols which prioritize energy savings over network throughput and packet latency. However, we argue that both network throughput and packet latency are critical for many sensor network applications, such as battlefield surveillance, real-time monitoring seismic waves, machine operations, bush fires, etc. Accurate and timely delivery of sensed data in these cases sometimes means the difference between life and death. In this paper, we propose a frequency division based DS-CDMA system which can simultaneously achieve high energy efficiency, high network throughput and low packet latency. These advantages are a result of applying frequency division to reduce the MAI in the system. By using an analytical model, we show that a small number of frequency channels can reduce MAI significantly. This paper makes the following contributions:

- Propose to use frequency division to reduce MAI in a wireless sensor network environment.
- A mathematical model to calculate the expected value of MAI at a given node in a uniformly distributed sensor node topology.
- Through discrete event simulation (using NS-2), we show that the proposed system can achieve less channel contention, lower packet latency, higher packet delivery ratio, and lower energy consumption.

Organization — The rest of this paper is organized as follows. Section II provides preliminary knowledge and the problems of using DS-CDMA system in sensor networks. Section III describes the proposed design architecture, analytical model and several important issues. Section IV provides simulation results and analysis. Section V describes related work. We conclude our paper in section VI with future research directions.

II. THE LIMITATIONS OF DS-CDMA SYSTEM

DS-CDMA system uses Spread Spectrum (SS) modulation technique, in which the baseband signal is spread using a Pseudo Noise (PN) code. The multi-user, *multiple access interference (MAI)* environment of DS-CDMA introduces significant challenges on how interference can be properly controlled. Consider a DSSS/BPSK (Direct Sequence Spread Spectrum/Binary Phase Shift Keying) system, let P_0 denote the average received power of the desired signal. Assume that there are k interferers with received powers $P_1, P_2, \ldots, P_k$, then the *effective bit energy-to-noise ratio* at the detector is given by [12]:

$$\mu \triangleq \frac{E_b}{N_{0\text{eff}}} = \left(\frac{2\sum_{i=1}^{k} P_i}{3LP_0} + \frac{1}{\mu_0} \right)^{-1} \tag{1}$$

where L is the processing gain, and $\mu_0 = E_b/N_0$ equals $E_b/N_{0\text{eff}}$ at the detector in the absence of interferers. The probability of bit error P_e with a given μ is then given by $P_e = \frac{1}{2}\text{erfc}(\sqrt{\mu})$ which is decreasing function of μ.

In a cellular DS-CDMA network, the MAI can be controlled by the base station by limiting the number of active nodes and requiring that all active nodes control their transmission power so that the received power at base station is the same. However, the same principle can not be applied to a practical sensor network.

The difficulty of using DS-CDMA system in a sensor network lies in the fact that a sensor network does not have a centralized base station which leads to the MAI being uncontrollable. Consider the situation in Figure 1, where sensors are randomly deployed and R_R represents the communication range. Each node has a number of neighbors situated at different distances. For example, A has neighbors B, E, F, D, and G, with each having different distance to A. Assume that each node uses the minimum required power to communicate with each other. When A is transmitting to a neighbor, the interference power caused by this transmission at other neighbors can have different values. Considering two simultaneous transmissions from $A \rightarrow B$ and $C \rightarrow D$, where distance $d_{AB} \gg d_{AD}$, the interference power at D caused by the *closer* neighbor A is much higher than that of the desired power from C, and this makes the desired signal hard to be recovered. However, if the transmission is $A \rightarrow E$ instead of $A \rightarrow B$, the interference caused to D's reception is negligible. The problem caused due to interference signal(s) drowning out desired signal at a receiver is a consequence of MAI. This example demonstrates that it is not possible to use power control to minimize the effect of MAI in a DS-CDMA sensor network. The MAI may cause significant degradation in network throughput and is considered the main problem prohibiting the usage of DS-CDMA in sensor networks.

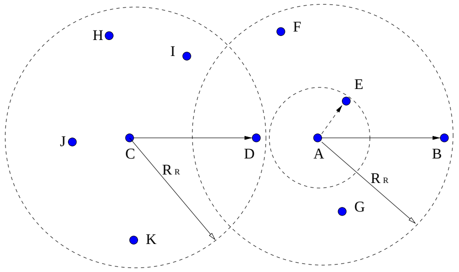

Fig. 1. *Example showing DS-CDMA MAI and near-far problem.*

III. THE PROPOSED DESIGN

In the last section, we discussed the limitations of using DS-CDMA system in sensor networks. The root cause of MAI lies in the fact that, unlike FDMA and TDMA channels, CDMA codes are not completely orthogonal. Completely orthogonal codes (e.g., Walsh codes) are normally used in synchronous systems. However, in asynchronous systems, perfect orthogonal codes are sub-optimal and exhibit high cross-correlation.

Because MAI is caused by the non-perfect orthogonality of CDMA codes, the rationale of our design is to *orthogonalize the reception* in the vicinity of a sensor node. In this paper, we propose to use frequency division to reduce the MAI. As most sensor network applications normally operate with low data rate, it is possible to use a narrow band CDMA system operating over multiple frequency channels. Let's assume that the data rate of the application is 20 Kbps, and we use 50 chip/bit PN code to spread the baseband signal. The resulting bandwidth is 1MHz. With 2.4GHz ISM band (2400MHz-2483.5MHz), we can have more than 80 frequency channels. We make the following assumptions in our design:

- Sensors are normally static nodes.
- A topology control protocol is available to limit the number of neighbors.
- Multiuser detection receivers are available but may only be monitoring a limited number (e.g., number of neighbors) of PN codes.
- Sensors can adjust their transmission power to reach different neighbors.

A. System Architecture and Channel Allocation Pattern

A set up phase is required for our sensor network architecture where, during this phase, frequency channels and PN codes are assigned to enable the nodes to communicate during steady state. This set up phase has been discussed in our earlier paper [16]. In this paper, we focus on the steady state operation which we will describe now. In our protocol design, each node is assigned a unique *receiving* frequency different to its neighbors. Each *directed* link is also assigned a unique PN code that is different from its adjacent links. Two directed links are adjacent if they have a common end node. Both frequency channels and PN codes can be re-used spatially. Orthogonalization in frequency also implies that reception and transmission can happen concurrently. When a node wants to transmit a packet to a neighbor, it synthesizes its transmitter to the corresponding receiving frequency of the neighbor and uses the pre-determined PN code with the neighbor to spread the baseband signal.

Without loss of generality, we use a regular graph shown in Figure 2 to explain the concept. The *receiving* frequency of each node is shown next to the node. The PN code used for each directed link is shown along the link. When A wants to transmit to D, it synthesizes its transmitter to $f5$ and uses $PN4$ to spread the data packet. Note this transmission does not cause interference to other neighbors such as C, B, G, F, E because their receivers are running on different receiving frequencies. Also note that B, F and D can transmit to A simultaneously because A's multiuser detection receiver can distinguish all its *neighbors'* transmissions concurrently. Note that A does not need to monitor the whole set of PN codes but only the set of codes that are employed by its immediate neighbors. A's transmission to D will not destroy A's reception from B, F and D even if they are happening in parallel because they are operating on different frequencies. Furthermore, the transmission signal from G to B will not contribute to the noise floor at A because it is operating on $f7$. To this end, we notice that MAI only occurs at a given receiving node (e.g., A) when multiple neighbors (e.g., B, F, D) transmit to this node (e.g., A) simultaneously. When these simultaneous transmissions occur, they are actually desired signals as they are all addressed to this node (e.g., A). With proper power control, the resulted MAI at this node (e.g., A) can be controlled at the lowest level. Those uncontrollable

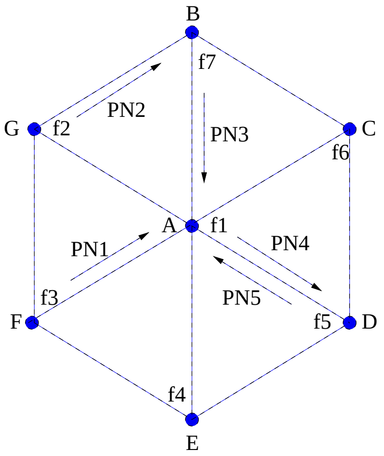

Fig. 2. *System architecture and channel allocation pattern.*

MAI presented in a pure DS-CDMA system, which is caused by the transmission between an interference node (e.g., G) and its neighbor (e.g., B but not A), is actually removed due to the frequency division. Note it is possible that some other nodes are transmitting with the same frequency in the network (as frequencies are reused spatially). But assuming that the channel allocation scheme (see next) can be met, these transmissions are normally far enough and the resulted interference are negligible. Because a node does not have to consider the interference caused by its transmission on the unintended receivers, it is much easier for a node to control its transmission power to guarantee that the transmitted signal arrives at the intended receiver with a certain power level, e.g., the *lowest receiving threshold*.

We represent a sensor network by a graph $G = (V, E)$, where V is the set of nodes, and E is the set of logical links. We assume only bilateral links exist. A logical link (a, b) means that node a considers node b as a neighbor if and only if node b also considers node a as a neighbor.

Figure 2 also shows the channel allocation pattern. The frequency channel allocation is a *two-hop vertex coloring* problem in graph theory: *where nodes sharing a common neighbor can not have the same color*. The minimum number of required frequencies (colors) k can be given from Brook and Vizing theorem [14]:

$$k = min\{\Delta(\Delta - 1) + 1, |V|\} \tag{2}$$

where Δ represents the node degree of the graph G.

There are several schemes for the PN code assignment: receiver-based, transmitter-based, or pairwise code assignment [10]. Since frequency channel assignment is receiver-based, PN code assignment should use either transmitter-based, where all neighbors of a given node have different codes for transmitting; or transmitter-receiver pair based, where no two adjacent directed links in the logical topology have the same code. Both schemes can be used. The transmitter based code assignment is also a two-hop coloring problem. We adopted the pairwise code assignment scheme (as shown in Figure 2) in our current design because it requires a smaller number of codes than the transmitter-based scheme.

By employing frequency division, our protocol design can achieve significant reduction in MAI and consequently less contention. This makes it possible to remove control packet (RTS/CTS) exchange which leads to higher packet delivery ratio, lower packet latency, and less energy consumption. frequency division also decreases the energy consumption due to reduction of overhearing.

B. Multiple Access Interference Modeling

In this section, we provide the analytical model for the mean MAI at a given node, and how the number of frequency channels can influence the mean MAI. Following assumptions are used in this analysis:

- Sensor nodes are randomly uniformly distributed.
- Each node transmits with an independent probability to a random neighbor.
- We assume a random frequency allocation pattern which represents the worst case comparing with the systematic frequency allocation pattern discussed in section III-A.

We assume that the node whose mean MAI we are interested to compute is located at the origin with receiving frequency f_0.

We assume a sensor network with h nodes which are randomly and uniformly deployed into a plane $\mathcal{R} \subseteq \mathbb{R}^2$. For convenience, we assume $\mathcal{R}$ to be a square $[0, d]^2$, having area $\|\mathcal{R}\| = d^2$, and suppose d and h increase together in such a manner that $h/\|\mathcal{R}\| \to \lambda$ where $0 < \lambda < \infty$. Let $\mathcal{S}$ denotes a bounded Borel subset of $\mathcal{R}$. For large d where $\|\mathcal{R}\| \gg \|\mathcal{S}\|$, and then the chance that $\mathcal{S}$ contains precisely k of the uniformly distributed nodes is given by [15]:

$$P[k \text{ in } \mathcal{S}] = \binom{n}{k} \left(\frac{\|\mathcal{S}\|}{\|\mathcal{R}\|}\right)^k \left(1 - \frac{\|\mathcal{S}\|}{\|\mathcal{R}\|}\right)^{h-k} \tag{3}$$

As $\mathcal{R}$ increases, the binomial distribution of equation 3 is well approximated by a Poisson process:

$$P[k \text{ in } \mathcal{S}] = \frac{(\lambda\|\mathcal{S}\|)^k}{k!} e^{-\lambda\|\mathcal{S}\|} \tag{4}$$

where λ equals the mean number of nodes per unit area of $\mathcal{R}$, or node density.

We first analyze the distribution of the interference power at the origin which is caused by an interference node. Assume that each node has a bounded normalized (The normalization is with respect to antenna gain, system loss, and wavelength) maximum transmission power P_T. Let P_R denote the lowest receiving threshold, then by using the propagation law, the maximum transmission range R_R is given by $R_R = \sqrt[n]{P_T/P_R}$, where n is the path loss exponent[1] and normally $2 < n < 6$. Let P_I be carrier sense threshold, then the interference range R_I is given by $R_I = \sqrt[n]{P_T/P_I}$.

We assume that each node has perfect power control so that the power level of the desired signal at the intended receiver equals to P_R. Now consider that an interference node i is transmitting to a random neighbor node j as shown in Figure 3. The transmission power of node i is a random variable that is dependent on the distance between node i and node j. We define this random variable as $\mathbf{x_{ij}}$, where

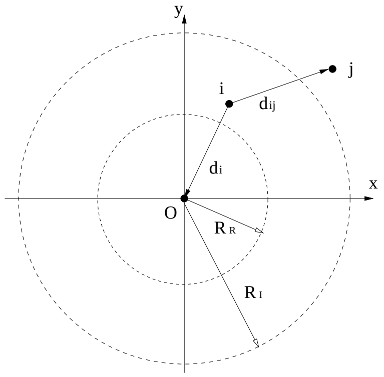

Fig. 3. *Interference model.*

$$\mathbf{x_{ij}} = P_R \mathbf{d_{ij}^n} \quad d_{ij} \in (0, R_R] \tag{5}$$

Note $\mathbf{d_{ij}}$ is also a random variable representing the inter-nodal distance. Assume that both the node at the origin O and node j use receiving frequency f_0. Now consider the interference power at the origin that is caused by transmission from node i to node j. We define this interference power as a random variable $\mathbf{z}$:

$$\mathbf{z} = \frac{\mathbf{x_{ij}}}{\mathbf{d_i^n}} = \frac{P_R \mathbf{d_{ij}^n}}{\mathbf{d_i^n}} \quad d_{ij} \in (0, R_R], d_i \in (0, R_I] \tag{6}$$

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[1] To make the moment generating function of the interference power exist, we assume that $n \neq 2$.

where random variable $\mathbf{d_i}$ denotes the distance of node i to the origin. We can prove (see [17]) that the density function of $\mathbf{z}$ is:

$$f_{\mathbf{z}}(z) = \begin{cases} \frac{\alpha}{2}\left(\frac{R_I}{R_R}\right)^2 P_R^{-\alpha} z^{\alpha-1} & 0 \leq z < a \\ \frac{\alpha}{2}\left(\frac{R_R}{R_I}\right)^2 P_R^{\alpha} z^{-\alpha-1} & a \leq z < b \end{cases} \tag{7}$$

where $a = P_R R_R^n / R_I^n$, $b = P_R R_R^n$, and $\alpha = 2/n$.

Now let E be a Poisson process in the plane with density λ. The probability law for E is determined by equation 4. We assume that the probability that a node is transmitting equals to p, then the set of transmitting nodes forms a Poisson process E_t with parameter $\lambda_t = \lambda p$. Further assume that there are M frequency channels. And each node selects a frequency channel for receiving with equal probability (note we assume a random selection scheme). The probability that a node is transmitting with a specific frequency (e.g., f_0) equals to $p' = p/M$. The set of transmitting nodes with a specific frequency also forms a Poisson process E_t' with parameter $\lambda_t' = \lambda p/M$. Now, with each sample function of E_t', we can associate the random variable

$$\Omega = \sum z_k \tag{8}$$

where the summation is over all points of the sample function of E_t' within the disk that is centered at origin with radius R_I, we denote the disk as $D(R_I)$. To find the expected value of MAI at the origin, we work with the moment generating function of Ω, denote as $\Phi_\Omega(s) = \mathbf{E}[e^{s\Omega}]$. The expected value can then be derived from the first derivative of $\Phi_\Omega(s)$ at $s = 0$. Using conditional expectations, $\Phi_\Omega(s)$ may be evaluated as

$$\begin{aligned} \Phi_\Omega(s) = \mathbf{E}[e^{s\Omega}] = \mathbf{E}[\mathbf{E}[e^{s\Omega} \mid k \text{ in } D(R_I)]] = \\ \sum_{k=0}^{\infty} \frac{e^{-\lambda_t' \pi R_I^2} (\lambda_t' \pi R_I^2)^k}{k!} \mathbf{E}[e^{s\Omega} \mid k \text{ in } D(R_I)] \end{aligned} \tag{9}$$

where 'k in $D(R_I)$' is the event that there are k transmitting nodes with the same frequency (f_0) in disk $D(R_I)$, and the expectation is over the random variable Ω.

Now, given that there are k transmitting nodes with a specific frequency (f_0) in disk $D(R_I)$, and since the moment generating function of the sum of a number of independent random variables is the product of the individual moment generating function, we have

$$\mathbf{E}[e^{s\Omega} \mid k \text{ in } D(R_I)] = \left(\int_0^\infty e^{sz} f_{\mathbf{z}}(z) dz \right)^k \tag{10}$$

Using equation 7 in above equation, and after some simplification and substitution, we obtain

$$\begin{aligned} \Phi_\Omega(s) = \exp\Bigg(\frac{\lambda p \pi R_I^2}{M} \Bigg(\frac{\alpha a^{-\alpha}}{2} \int_0^a e^{sz} z^{\alpha-1} dz \\ + \frac{\alpha a^{\alpha}}{2} \int_a^b e^{sz} z^{-\alpha-1} dz \; - \; 1 \Bigg) \Bigg) \end{aligned} \tag{11}$$

We then obtain the expected value of Ω as below

$$\begin{aligned} \eta = \Phi_\Omega'(0) = \frac{\alpha a \lambda p \pi R_I^2}{2M} \left(\frac{1}{\alpha+1} + \frac{1-(a/b)^{\alpha-1}}{\alpha-1} \right) \\ \times \exp\left(-\frac{\lambda p \pi R_I^2}{2M} \left(\frac{a}{b} \right)^{\alpha} \right) \end{aligned} \tag{12}$$

The above equation gives the expected value of the mean multiple access interference power at a given node in relation to the number of frequency channels (M). As an example, Figure 4 shows the mean MAI versus the number of frequency channels with following parameters: $\lambda = 0.01$, $P_R = -70dBm$, $R_R = 25m$, $R_I = 50m$, and $n = 4$. We see that the mean MAI reduces sharply with the employment of a small number of frequency channels. For example, the mean MAI with $p = 1$ and one frequency is -62.2dBm, the mean MAI reduces to -72.1dBm with 10 frequency channels. This almost equals to 10 times reduction. Further, our simulations (presented in section IV) shows that the reduction of MAI leads to high packet delivery ratio, low packet latency, and less energy consumption.

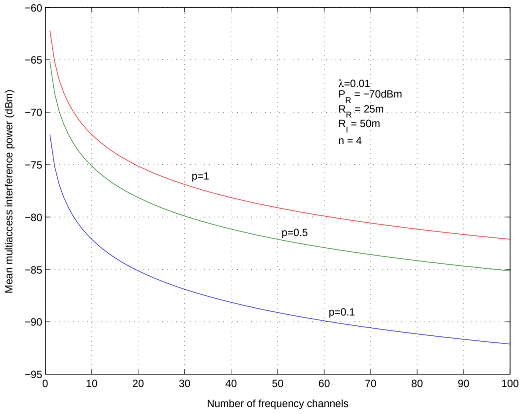

Fig. 4. *Mean MAI versus number of frequency channels*

C. Other System Issues

There are several important challenges in our design but detailed discussion is out of the scope of this paper. Here we provide a brief description.

1) Channel Allocation Protocol: Sensor networks are expected to have hundreds if not thousands of nodes. So it is infeasible to assign each node a unique frequency channel or spreading code. To achieve a flexible and scalable sensor network, limited number of frequency channels and spreading codes must be reused spatially.

We implemented a simple heuristic channel assignment (both frequency and PN code) scheme in our design, where each node negotiates with each neighbor individually for the channel assignment during the network setup phase (see [16]). A more efficient algorithm is still under design.

2) Broadcasting Traffic: One of the problems of using frequency division is how to deal with broadcasting traffic. Here we propose three approaches: a) Each node transmits a broadcast packet to its neighbors with multiple unicasts. b) Each node employs a second transceiver[2]. This second transceiver is dedicated to broadcast traffic (and possible control purpose) and synthesizes to a default frequency channel. With this approach, each node employs a different transmitting PN code for broadcasting, and monitors the broadcasting PN codes of its immediate neighbors. c) Each node employs a second transceiver. But the transmission scheme is the same as IEEE 802.11, where each node transmits broadcast packets with the same frequency and the same PN code (Note data spreading in this case is only for better channel performance but not for multiple access). We are currently making a detailed comparison of these three schemes and will report the result in a future paper.

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[2] Multiple transceiver design is popular in sensors. For example, Mica mote and Pico Node are all equipped with dual transceivers.

3) Idle Energy Consumption: As stated before, energy efficiency is crucial to prolong the lifetime of the sensor network. To achieve significant energy savings, a node should turn off its radio when it does not participate in data forwarding or no event occurs. The simplest way is to allow each node to sleep and wake up periodically as proposed in SMAC [7]. With proper coordination, nodes can sleep and wake up with the same duty cycle. Guo [9] *et al.* proposed a super low power radio called *wake-up radio* that can allow the normal radio to power down during idle listening time. The *wake-up radio* serves as a *small ear* and keeps monitoring the channel signal on a super low power. The monitoring power is around $1\mu W$. Schurgers *et al.* [8] proposed a technique to efficiently wake up nodes from deep sleep state by separating the data and wakeup with two radios. The wakeup radio operates on low power listening mode and uses a periodic sleep-wakeup scheme similar to [7]. The wakeup radio does not assume any specific protocols at the MAC layer so it can work with different MAC protocols.

Although our design is targeting high network throughput and low latency, we would like to emphasize that our design can also accommodate one of the these sleep-wakeup schemes. The combination of our design with one of these schemes can achieve both high network throughput and energy efficiency.

IV. SIMULATIONS AND ANALYSIS

A simulation testbed has been implemented in NS-2. The simulations focus on how the system performance and energy consumption are influenced by the number of frequency channels.

A. Simulation Setup

All simulations are conducted based on a randomly generated topology where 100 nodes are uniformly randomly deployed in a $100m \times 100m$ square area. We adopted a simple topology control protocol proposed in [2] called *K-Neigh* to guarantee that the network is connected with high probability. With this approach, each node keeps up to $k = 9$ neighbors and remove those neighbors with unidirectional links.

We focus on one-hop performance measurement in our simulation. Instead of measuring the system capacity or throughput directly, we measured the packet drop rate with different packet generation rate. In our simulations, each node randomly selects a neighbor and transmits 100 packets to this neighbor. CBR traffic is used but each packet's departure time is randomized according to a uniform distribution (refer to NS-2 manual). With this randomization, the packets generated from each node can be well approximated as a Poisson process. Different transmission patterns are randomly generated where each node can transmit to different neighbors. For each run, there are 10000 packets (100 nodes × 100 packet/node) transmitted in the whole network. The start time of each node's transmission is also randomized according to the packet transmission interval. This is to ensure that each node can start at similar time but not exactly the same time which may influence the performance of the contention based protocol.

One of the most important parameter in the simulation is the *MAI threshold*, which is the ratio between the total interference signal power and the desired signal power. We consider a simple DS-CDMA system, where BPSK modulation and a convolution code with rate $1/2$ are used. Further assume that the processing gain $L = 50$ and the required $E_b/N_{0\text{eff}}$ is 5 dB. Ignoring the thermal noise, the MAI threshold is calculated using equation 1:

$$\textit{MAI Threshold} = \frac{\sum_{i=1}^{k} P_i}{P_0} = 23.72 \tag{13}$$

where this number represents when the ratio between the interference signal power and the desired signal power is larger than 23.72, the packet will be destroyed due to the MAI.

Comparisons with a well known contention based MAC protocol, SMAC [7], are studied. The transmission range of SMAC is calculated according to $R_R = \sqrt{k/\pi\lambda}$, where $k = 9$ denotes the number of neighbors and $\lambda = 0.01$ denotes the node density. SMAC is especially designed for energy saving purposes based on IEEE 802.11 standard and performs similar to IEEE 802.11. In our simulations, we assume that SMAC also employs spread spectrum as IEEE 802.11 for better channel performance. The parameters used in our simulations are shown in Table I.

TABLE I

PARAMETERS USED IN SIMULATIONS.

Processing Gain	50
MAI Threshold	23.72
Data Rate	20 Kbps
Data Packet Size	50 Bytes
Control Packet (RTS/CTS) Size	10 Bytes
Propagation Model	Log distance path loss
Reference Distance	1 meter
Path Loss Exponent	3
Antenna Gain	1
System Loss	1
Rx Threshold	1e-10 W
Carrier Sense Threshold	1e-11 W
Tx Electronic Power	10e-3 W
Rx Electronic Power	15e-3 W
Max Radio Power	5e-3 W

B. Simulation Results

From now onward, we refer our protocol as CDMA sensor MAC (CSMAC) [16] and m represents the number of frequency channels.

1) Comparison with Contention Based MAC Protocol: We first demonstrate the performance comparison between SMAC, CSMAC with $m = 1$, and CSMAC with $m = 10$. A randomly generated traffic pattern is used in this simulation. Figure 5 shows the packet drop rate comparison, where each point corresponds to 5 runs. We see that SMAC and CSMAC with $m = 1$ exhibit similar performance with low traffic load, e.g., when the packet generation rate is less than 0.1 packet/s. The graph also shows that the drop rate of SMAC reaches 4% when the packet generation rate reaches 0.1. While CSMAC with $m = 1$ still achieves drop rate 1% even when the traffic load reaches 0.5. When the packet generation rate is over 0.1, the drop rate of SMAC increases sharply and reaches

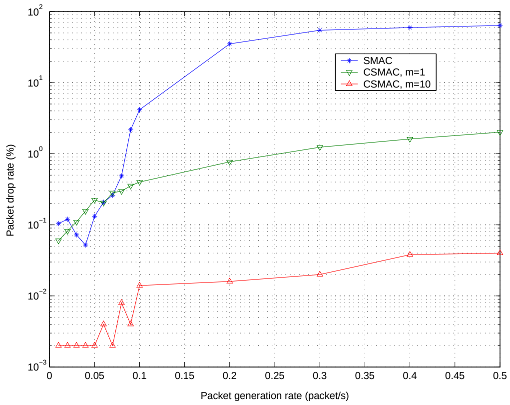

Fig. 5. *Packet drop rate comparison with low traffic*

an unacceptable level. For example, the drop rate is 35% when the packet generation rate is 0.2. The graph also shows that CSMAC with $m = 10$ performs much better than $m = 1$, the drop rate is only 0.04% with 0.5 packet/s generation rate.

Figure 6 shows the average one-hop latency for the whole network (CSMAC with $m = 10$ performs the same as $m = 1$ and not plotted in the graph). We conducted 5 runs and calculated the average value of the one-hop latency for all correctly received packets for each run. The plotted values represent the average values of these 5 runs. It is to be expected that CSMAC performs much better than SMAC because CSMAC does not need to reserve media for a packet transmission. On the contrary, each node has to contend for the media to transmit with SMAC. The graph shows that the one hop latency of SMAC increases steadily with the increase of traffic load. We found that the average one hop latency of SMAC reaches several seconds or even higher when the traffic load is over 0.1 packet/s (not plotted in the graph). On the contrary, the one hop latency of CSMAC is constant and is not influenced by the increases of traffic load. Because CSMAC does not need to reserve media for a transmission. A node simply transmits a packet if it has one.

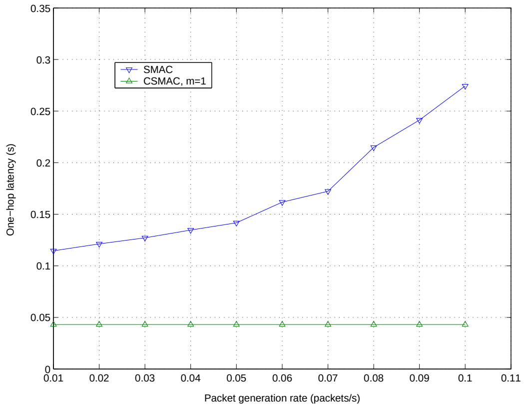

Fig. 6. *Latency comparison*

2) Energy Consumption versus Frequency Division: We next measured the communication energy efficiency of CSMAC with different number of frequency channels. The idle energy consumption is not included in this study as it only adds a constant mean value to our results and it may hide the effect of communication energy consumption. Figure 7 shows the average energy consumption of each node with different number of frequencies and Figure 8 shows the energy consumption of the whole network versus the number of frequency channels. We see that the energy consumption is decreased sharply with the employment of only a small number of frequency channels. For example, CSMAC with $m = 10$ and $m = 30$ achieves 84% and 91% energy savings over $m = 1$. This is because the overhearing is reduced significantly due to the frequency division. The energy savings become insignificant with further increases in number of frequencies.

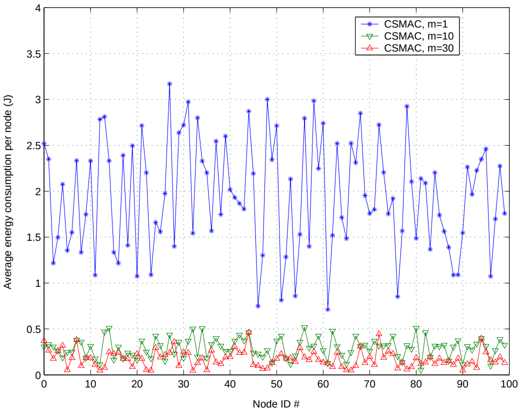

Fig. 7. *Energy consumption comparison for each node*

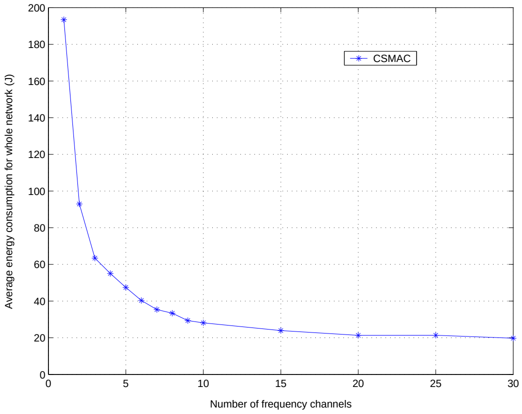

Fig. 8. *Average energy consumption for the whole network versus number of frequency channels*

3) Influence of Number of Frequency Channels on Network Performance: We study the influence of the number of frequency channels on the packet drop rate with high traffic load. We randomly generated 5 different traffic patterns. For each traffic pattern, a node transmits to a different neighbor. Figure 9 plotted the average packet drop rate for all of these 5 different traffic patterns. The first observation we make from Figure 9 is that CSMAC with $m = 1$ performs poorly when the traffic increases. For example, the average packet drop rate increases from 3.85% to 20% when the packet generation rate increases from 1 to 5. These results proved our discussions in section II that the limitation of using DS-CDMA in sensor network is due to the MAI. The second observation we make from Figure 9 is that a small number of frequency channels can reduce the packet drop rate significantly. For example, when $m = 5$, the average packet drop rate is reduced from 50.9% to 7.9% with 20 packet/s traffic load. When $m = 10$ and $m = 30$, the drop rate is reduced to 5.72% and 0.98% respectively. We see that these results

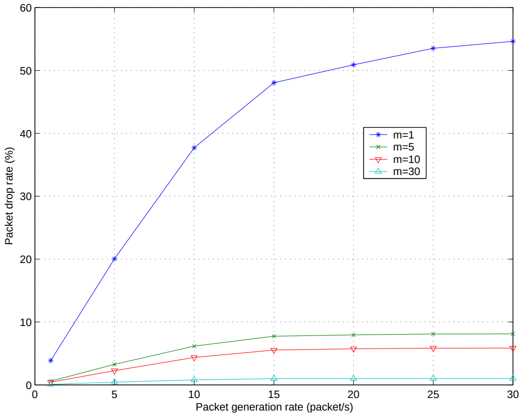

Fig. 9. *Packet drop rate comparison with high traffic*

show a similar trend to our mathematical modeling in section III-B, where the MAI is reduced significantly with the employment of a small number of frequency channels. The reflection of MAI reduction on this simulation is the reduction of packet drop rate. The third observation we make from Figure 9 is, on average, the more frequency channels, the lower packet drop rate. We see that on average, $m = 30$ performs better than that of $m = 5$ and $m = 10$. But the improvement is not as significant as we see from $m = 1$ to $m = 5$. This also seems to follow the same trend as our modeling in section III-B and Figure 4. More simulation results can be found in [17].

V. RELATED WORK

DS-CDMA system and MAI related problems have been extensively studied on cellular networks which are infrastructure based. Mobile nodes communicate with base station directly and energy consumption is not a critical concern in either mobile nodes or base stations. However, the problem in sensor networks differs from the traditional framework in terms of limited resources (e.g. energy, processing) of sensor nodes, less mobility, and lack of centralized base stations. All these factors make the research problems in DS-CDMA based sensor networks different from the traditional cellular based DS-CDMA networks.

Spread-spectrum techniques have been employed in IEEE 802.11b standard. The primary issue addressed in IEEE 802.11b is to reduce the multi-path effects in a heterogeneous environment. Data spreading results in greater immunity to radio frequency interference as compared to narrow-band signaling. Because IEEE 802.11b is a contention based protocol, MAI is not an issue because concurrent transmissions are not allowed in the vicinity of potential interference range.

Muqattash and Krunz [3] proposed a CDMA-based MAC protocol for wireless ad hoc networks where out-of-band RTS/CTS are used to dynamically bound the transmission power of a node in the vicinity of a receiver. Both RTS and CTS are enlarged to accommodate MAI related information. However, our design goal is to remove control packets for energy savings. De *et al.* characterized the MAI in wireless CDMA sensor networks and studied the tradeoff between interference and network connectivity. Their study revealed that high network connectivity can not be achieved without significantly increased MAI with random topology. To achieve high network connectivity, and low MAI, nodes should be selectively activated such that *the set of active nodes at any time lie on the vertexes of a regular polygon (e.g., square grid, hexagon, or equilateral triangle)*, which is not very practical for randomly deployed sensor networks. Liu and Asada [5] proposed an energy efficient DS-CDMA system for sensor networks by using spreading code with more ‘0’ bits and employing on-off keying. Sousa [11] *et al.* characterized the optimum transmission ranges to maximize the throughput for a directed-sequence spread-spectrum multi-hop packet radio network. Their work assumes that each node has equal transmission power and no frequency division is used, both of these assumptions are different from ours. Guo *et al.* [9] proposed a set of low power MAC design principles targeting at multi-hop wireless sensor networks. Different MAC protocols have been proposed for sensor networks, including contention based [6][7], and contentionless [1]. Interestingly, SMACS [1] also employed frequency division but assumes a TDMA and narrow band system.

VI. CONCLUDING REMARKS AND FUTURE RESEARCH

In this paper, we propose to use frequency division to reduce MAI in a DS-CDMA sensor network to achieve less channel contention, low packet latency, high packet delivery ratio, and less energy consumption. By employing frequency division, the uncontrollable MAI encountered in a pure DS-CDMA system is effectively reduced and great improvement in network throughput and system capacity can be achieved. We characterize analytically the expected value of MAI at a given node in relation to the number of frequency channels. Our mathematical model shows that a limited number of frequency channels can reduce the MAI significantly. Simulation results show a similar trend with the measured packet drop rate.

Future work will include efficient channel allocation protocol and comparison of broadcasting schemes that we discussed in section III-C. Further development of our mathematical model for the network throughput and system capacity based on our current result is also under consideration.

VII. ACKNOWLEDGEMENT

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