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

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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.

1 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 [14] 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. Blough *et al.* [5] proved the crude lower bound that no contentions occur in a wireless channel with following lemma:

Lemma 1 *Let $\bar{t}$ be the time necessary to transmit a packet. For $d = m\bar{t}$, the probability that no contention will occur in a wireless channel is strictly grater than $exp(-\frac{3h(h-1)}{2m})$, where h denotes the number of nodes that are contending for the channel.*

An example was also given with 33 contending nodes, where d must be around $16000\bar{t}$ to achieve a probabilistic guarantee of no contention of at least 0.9. Assume that $\bar{t}$ represents the transmission time of a packet with 802.11 data rate (2Mbps) in above example. Now considering the same packet is transmitted with sensor network data rate (20Kbps). During the same period of time d, the probability of no collision will occur is 5.023×10^{-5}, which is almost zero. In other word, collisions will always occur. The consequence is that control packet (RTS/CTS) exchange is inevitable to avoid collisions. Moreover, some energy efficient algorithms proposed for contention based protocols for sensor network require the information embedded in RTS/CTS packets. For example, SMAC [19] 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. We believe that the characteristics of the traffic pattern in sensor networks demand both energy and latency efficiency. For example, when no event occurs, all sensors are at monitoring state and their radios should be turned off for energy saving purpose. When one or more events occur, sensors around the vicinity of the event(s) may be required to transmit simultaneously to achieve collaborative signal processing. Normally most of these sensors are physical nearby neighbors. Moreover, these packets may follow similar paths back to the sink, and the contentions along the way back are also high. Besides, trade off latency not always mean energy efficiency. For example, packet collision is a normal case in contention based protocols in higher traffic scenario. Collided packets must be retransmitted which leads more energy are consumed. In addition, a sensor has limited buffer space, if a packet can not be transmitted in time, following packets may be dropped due to the overflow of the buffer space. Dropped packets may be re-transmitted and extra energy are wasted.

As an alternative to contention based MAC designs, using direct sequence code division multiple access (DS-CDMA) based system in ad hoc and sensor networks have been proposed in literature [6][7][9][22]. It is well known that the *multiple access interference (MAI)* is the key factor in determining the network performance (e.g., throughput) in a DS-CDMA system. The inherent randomized distribution of sensor nodes and lack of centralized base station make the effective control of interference more difficult. 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. Our design objectives are as follows:

- Control packet (RTS/CTS) exchange should be avoided to achieve both energy and latency efficiency.
- MAI must be properly controlled to achieve less channel contention, lower packet latency, higher packet delivery ratio, and lower energy consumption.
- The proposed system must be able to accommodate high traffic.
- For practical implementation purpose, the receiver should not be required to monitoring the whole PN (Pseudo Noise) code sets.
- To achieve further energy savings, a sleep-wakeup scheme may be adopted from literature to reduce idle energy consumption in case of variable traffic.

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 2.2 provides preliminary knowledge and the problems of using DS-CDMA system in sensor networks. Section 3 describes the proposed design architecture, analytical model and several important issues. Section 4 provides simulation results and analysis. Section 5 describes the related work. We conclude our paper in section 6 with future research directions.

2 Preliminaries

In this section, we provide a brief introduction of DS-CDMA system and we then discuss the limitations of using DS-CDMA system in ad hoc and sensor networks, specially, the multiple access interference (MAI) and near-far problem.

2.1 DS-CDMA System

Code division multiple access (CDMA) communication systems were original designed for military usage for either 1) to provide resistance to hostile jamming, 2) to hide the signal by transmitting it at low power and, thus, making it difficult for an unintended listener to detect it presence in noise, or 3) to make it possible for multiple users to communicate through the same channel [29].

DS-CDMA based system uses Spread Spectrum (SS) modulation technique, in which the baseband signal is spread (e.g., multiplied by) using a Pseudo Noise (PN) code. A PN code is a sequence of chips valued -1 and 1 (polar) or 0 and 1 (non-polar). Such bit-sequences have noise-like properties like spectral flatness and low cross and auto correlation values, and thus complicate jamming or detection by non-target receivers [40]. In practice, the PN sequence selected must have both good cross-correlation and auto-correlation. The receiver uses cross-correlation to separate the appropriate signal from other interfering signals (those destined for other receivers), and uses auto-correlation to reject multi-path interference. Specific PN codes include Walsh codes, M-sequences, Gold codes and Kasami codes.

Spread spectrum has many properties that makes it particular attractive for wireless environment. The most important advantage is its inherent interference rejection capability. Not only can a particular spread spectrum signal be recovered from a number of other spread spectrum signals, it is also possible to completely recover a spread spectrum signal even when it is jammed by a narrow band interferer [35]. Resistance to multi-path fading is another fundamental feature of spread spectrum modulation.

The main parameter of a DS-CDMA system is the *processing gain*, which is defined as the ratio of spread data rate to the baseband data rate: $L = B_t/B_i$, where L is the processing gain, B_t is the bandwidth of spread signal, and B_i is the bandwidth of baseband signal. Processing gain determines the number of simultaneous transmissions that can be allowed in a system.

2.2 The Limitations of DS-CDMA System

Despite DS-CDMA system provides superior characteristics, its multi-user, *multi-access interference (MAI)* environment introduces significant challenges on how interference can be properly controlled. Considering a DSSS/BPSK (Direct Sequence Spread Spectrum/Binary Phase Shift Keying) system, let P_0 denotes 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 [30]:

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

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:

$$P_e = \frac{1}{2}\text{erfc}(\sqrt{\mu}) = Q\left(\frac{1}{\sqrt{\frac{\sum_{i=1}^{k} P_i}{3LP_0} + \frac{N_0}{2E_b}}} \right) \tag{2}$$

where erfc$(\cdot)$ is the complementary error function and $Q(\cdot)$ is the Q-Function. We see that P_e is the decreasing function of μ. If we assume that all signals (both desired and interferers) provide equal power at the detector, the above equation can be simplified to:

$$P_e = Q\left(\frac{1}{\sqrt{\frac{k}{3L} + \frac{N_0}{2E_b}}} \right) \tag{3}$$

In a interference limited DS-CDMA system, the thermal noise is not a factor, E_b/N_0 tends to infinity, above equation can be further simplified to:

$$P_e = Q\left(\sqrt{\frac{3L}{k}} \right) \tag{4}$$

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. The consequence is that the system performance is compromised severely especially in higher traffic scenario. In a practical sensor network, where nodes are normally randomly deployed, each transmitting node can transmit to multiple receivers and each receiving node can receive from multiple transmitters. It is infeasible to implement a power control scheme to guarantee that each receiver receives *all* signals (both desired and interferers) with *equal* power. In addition, each node may transmit to a random neighbor with random probability at any given time. The number of active nodes can not be controlled without using RTS/CTS in a potential interference vicinity. 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 and is called DS-CDMA *near-far* effect in literature. Near-far problem also implies that transmission and reception can not happen simultaneously. Because the transmitter power is too high that it will drown out any receiving signals. 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.

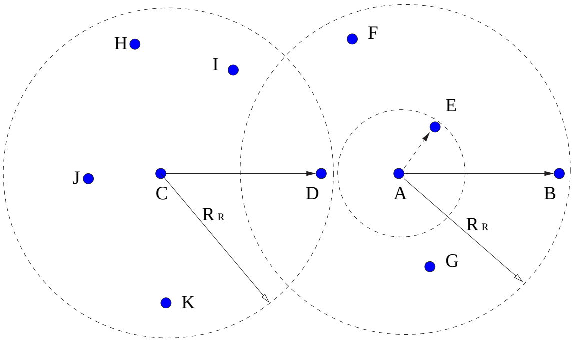

Figure 1: *Example showing the CDMA MAI and near-far problem.*

3 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. Short PN sequence can also be used. For example, the *minimum total-squared-correlation (minTSC) codes* [31] with chip length $L = 15$ can serve upto $2^{L-1} = 2^{14}$ [7] users. The advantage of using minTSC codes is its flexibility of accommodating number of users. But the system may be overloaded and the cross correlation may be high. Assuming with low probability that all users can be active simultaneously, the system can still achieve desirable bit-error-rate (BER). Moreover, the advantage of using frequency division is that the required bandwidth need not to be contiguous and different users can be allotted different frequencies depending on their requirements. 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.

3.1 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 [41]. 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

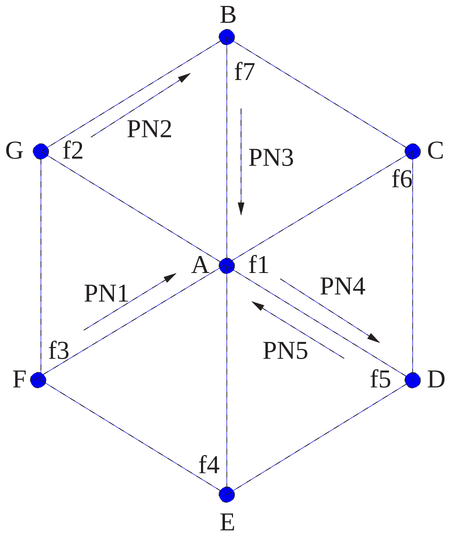

Figure 2: *System architecture and channel allocation pattern.*

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 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*. With above analysis, we may find out the number of simultaneous transmissions that a node can support. Assume that a given node has N_u neighbors and each neighbor can transmit signal to this node with the same power level simultaneously. The desired *signal-to-noise interference power ratio* at the receiver is given by [29][35]:

$$SINR = \frac{P_S}{P_N} = \frac{P_S}{(N_u - 1)P_S} = \frac{1}{N_u - 1} \tag{5}$$

where P_S/P_N can be expressed with reciprocal:

$$\left(\frac{P_N}{P_S}\right)_{dB} = \left(\frac{W}{R}\right)_{dB} + (CG)_{dB} - \left(\frac{E_b}{I_0}\right)_{dB} \tag{6}$$

where $(W/R)_{dB}$ denotes the processing gain (L in equation 1), $CG = R_c d^H_{min}$ is the coding gain that is defined by the code rate R_c and minimum Hamming distance d^H_{min} of the code, E_b/I_0 is the ratio between the mean energy per bit to the power spectral density of the interference. For example, assume processing gain $L = W/R = 50$, E_b/I_0 equals to 10 dB and coding gain is 6 dB, the number of simultaneous transmissions a node can support is 21.

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 3 shows the frequency channel allocation pattern with a regular triangular topology of sensors, where each sensor has exactly six neighbors (note with a random deployment, the number of neighbors can be decided by a topology control protocol). We see that 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 [36]:

$$k = min\{\Delta(\Delta - 1) + 1, |V|\} \tag{7}$$

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 [25]. 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 (edge) based, where no two adjacent links (edges) in the logical topology have the same code (color). Both schemes can be used. The transmitter based code assignment is also a two-hop

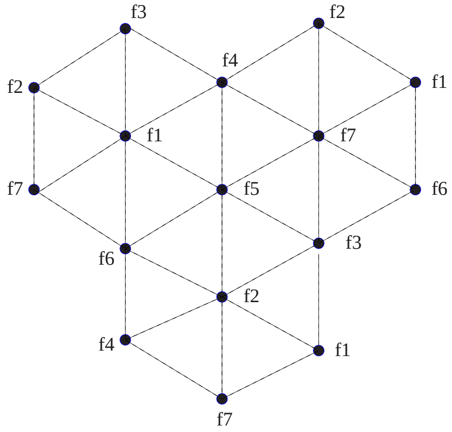

Figure 3: *Frequency allocation pattern – Two-hop vertex coloring.*

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.

3.2 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 3.1.

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

3.2.1 System Model

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 $h/\|\mathcal{R}\| \rightarrow \lambda$ 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 [39]:

$$P[k \text{ in } \mathcal{S}] = \binom{n}{k} \left(\frac{\|\mathcal{S}\|}{\|\mathcal{R}\|} \right)^k \left(1 - \frac{\|\mathcal{S}\|}{\|\mathcal{R}\|} \right)^{h-k} \quad (8)$$

As $\mathcal{R}$ increases, the binomial distribution of equation 8 is well approximated by a Poisson process:

$$P[k \text{ in } \mathcal{S}] = \frac{(\lambda \|\mathcal{S}\|)^k}{k!} e^{-\lambda \|\mathcal{S}\|} \tag{9}$$

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

3.2.2 The Distribution of Interference Power

We first analyze the distribution of the interference power at the origin which is caused by an interference node[1]. 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[2] and normally $2 < n < 6$. Let P_I be carrier sense threshold, then the interference range R_I is given by $R_I = \sqrt[n]{P_T/P_I}$, normally $R_I \approx 2R_R$.

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 4. 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 $\mathbf{x}$, where

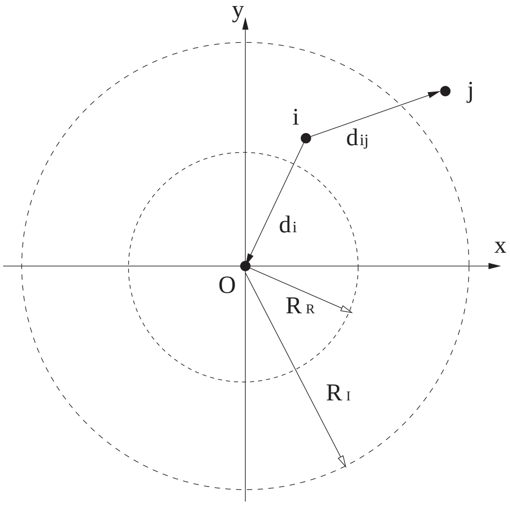

Figure 4: *Interference model.*

$$\mathbf{x_{ij}} = P_R \mathbf{d_{ij}^n} \quad d_{ij} \in (0, R_R] \tag{10}$$

Note $\mathbf{d_{ij}}$ is also a random variable representing the inter-nodal distance. Let B_a a disk centered at node i with radius a, and assume that there are k nodes are covered by B_a. Due to nature of Poisson process, the distribution of the locations of these k nodes is that of k independent and identically (iid) distributed points with uniform distribution. Let random variable $\mathbf{d}$ denotes the distance between i and j, the cumulative distribution function (cdf) of $\mathbf{d}$ under uniform random placement in a two-dimensional plane is given by

$$F_{\mathbf{d}}(d) = \begin{cases} \frac{d^2}{a^2} & d \in (0, a] \\ 1 & d > a \\ 0 & d < 0 \end{cases} \tag{11}$$

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[1] The analysis in this subsection is similar to [7] but we adopted a simpler approach.

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

The correspondent probability density function (pdf) of $\mathbf{d}$ is then evaluated by

$$f_{\mathbf{d}}(d) = \begin{cases} \frac{2d}{a^2} & d \in (0, a] \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

We now define a random variable $\mathbf{y} \triangleq \mathbf{d}^n$. Using equation 11 and we get the cdf of $\mathbf{y}$

$$F_{\mathbf{y}}(y) = \begin{cases} \frac{y^{\frac{2}{n}}}{a^2} & y \in (0, a^n] \\ 1 & y > a^n \\ 0 & y < 0 \end{cases} \tag{13}$$

and pdf

$$f_{\mathbf{y}}(y) = \begin{cases} \frac{2y^{\frac{2}{n}-1}}{na^2} & y \in (0, a^n] \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

From equation 10 we can see that $\mathbf{d_{ij}^n} = \mathbf{x_{ij}}/P_R$, use it in equation 13 and differentiate it and we get the density function of $\mathbf{x}$

$$f_{\mathbf{x}}(x) = \begin{cases} \frac{2x^{\frac{2}{n}-1}}{nP_R^{\frac{2}{n}} R_R^2} & x \in (0, P_R R_R^n] \\ 0 & \text{otherwise} \end{cases} \tag{15}$$

We 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 $\mathbf{z}$:

$$\mathbf{z} = \frac{\mathbf{x_{ij}}}{\mathbf{d_i^n}} = \frac{P_R \mathbf{d_{ij}^n}}{\mathbf{d_i^n}} \quad d_{ij} \in (0, R_R], d_i \in (0, R_I] \tag{16}$$

where random variable $\mathbf{d_i}$ denotes the distance of node i to the origin. Note that $\mathbf{d_i}$ also follows the same cdf and pdf as shown in equation 11 and 12. We now need to find the distribution and density function of $\mathbf{z}$. Because R_R and R_I are bounded, $\mathbf{z}$ has two integration zones: $0 \leq z < P_R R_R^n / R_I^n$ and $P_R R_R^n / R_I^n \leq z < P_R R_R^n$. The cdf of $\mathbf{z}$ is given by:

$$F_{\mathbf{z}}(z \quad | \quad 0 \leq z < P_R R_R^n / R_I^n) = \int_{y=0}^{R_I^n} \int_{x=0}^{yz} f_{\mathbf{x}}(x) f_{\mathbf{y}}(y) dx dy = \frac{1}{2} \left(\frac{R_I}{R_R} \right)^2 \left(\frac{z}{P_R} \right)^{\frac{2}{n}} \tag{17}$$

$$F_{\mathbf{z}}(z \quad | \quad P_R R_R^n / R_I^n \leq z < P_R R_R^n) = \int_{y=0}^{R_I^n} \int_{x=0}^{\frac{P_R R_R^n}{R_I^n} y} f_{\mathbf{x}}(x) f_{\mathbf{y}}(y) dx dy$$

$$+ \int_{x=0}^{P_R R_R^n} \int_{y=\frac{x}{z}}^{\frac{R_I^n}{P_R R_R^n} x} f_{\mathbf{x}}(x) f_{\mathbf{y}}(y) dy dx = 1 - \frac{1}{2} \left(\frac{R_R}{R_I} \right)^2 \left(\frac{P_R}{z} \right)^{\frac{2}{n}} \tag{18}$$

The density function of $\mathbf{z}$ is then given by:

$$f_{\mathbf{z}}(z) = \begin{cases} \frac{1}{n} (\frac{R_I}{R_R})^2 P_R^{-\frac{2}{n}} z^{\frac{2}{n}-1} & 0 \leq z < \frac{P_R R_R^n}{R_I^n} \\ \frac{1}{n} (\frac{R_R}{R_I})^2 P_R^{\frac{2}{n}} z^{-\frac{2}{n}-1} & \frac{P_R R_R^n}{R_I^n} \leq z < P_R R_R^n \end{cases} \tag{19}$$

3.2.3 Mean MAI At A Given Node

Now let E be a Poisson process in the plane with density λ. The probability law for E is determined by equation 9. 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

$$\Omega = \sum z_k \tag{20}$$

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 $\Phi_\Omega(s)$. The expected value can then be derived from the first derivative of $\Phi_\Omega(s)$ at $s = 0$. We know that the moment generating function is related to Laplace transform

$$\Phi_\Omega(s) = \int_0^\infty e^{s\omega} f_\Omega(\omega) d\omega = \mathbf{E}[e^{s\Omega}] \quad s \geq 0 \tag{21}$$

where $f_\Omega(\omega)$ is the density function of Ω. Using conditional expectations, this may be evaluated as

$$\mathbf{E}[e^{s\Omega}] = \mathbf{E}[\mathbf{E}[e^{s\Omega} \mid k \text{ in } D(R_I)]] = \sum_{k=0}^{\infty} \frac{e^{-\lambda'_t \pi R_I^2} (\lambda'_t \pi R_I^2)^k}{k!} \mathbf{E}[e^{s\Omega} \mid k \text{ in } D(R_I)] \tag{22}$$

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

$$\mathbf{E}[e^{s\Omega} \mid k \text{ in } D(R_I)] = \left(\int_0^\infty e^{sz} f_{\mathbf{z}}(z) dz \right)^k \tag{23}$$

Using equation 19 in above equation, and after some simplification and substitution, we obtain

$$\Phi_\Omega(s) = \exp\left(\frac{\lambda p \pi R_I^2}{M} \left(\frac{\alpha a^{-\alpha}}{2} \int_0^a e^{sz} z^{\alpha-1} dz + \frac{\alpha a^\alpha}{2} \int_a^b e^{sz} z^{-\alpha-1} dz \; - \; 1 \right) \right) \tag{24}$$

where $a = P_R R_R^n / R_I^n$, $b = P_R R_R^n$, and $\alpha = 2/n$. We then obtain the expected value of Ω as below

$$\eta = \frac{d\Phi_\Omega(s)}{ds}\Big|_{s=0} = \Phi'_\Omega(0) = \frac{\alpha a \lambda p \pi R_I^2}{2M} \left(\frac{1}{\alpha+1} + \frac{1-(a/b)^{\alpha-1}}{\alpha-1} \right) \times \exp\left(-\frac{\lambda p \pi R_I^2}{2M} \left(\frac{a}{b} \right)^\alpha \right) \tag{25}$$

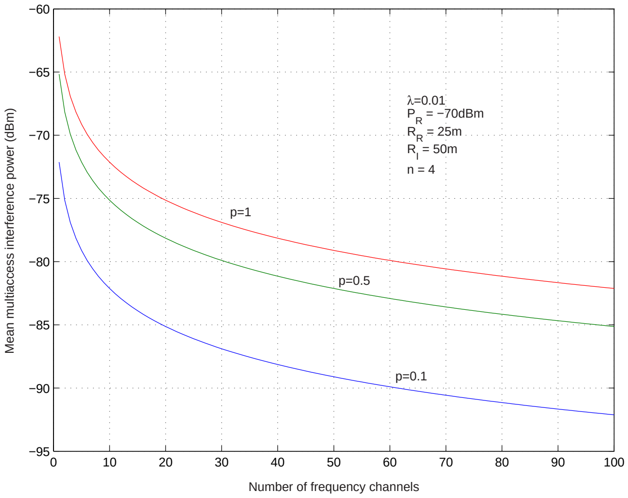

Figure 5: *Mean MAI versus number of frequency channels*

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. As an example, Figure 5 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 4) shows that the reduction of MAI leads to high packet delivery ratio, low packet latency, and less energy consumption.

3.3 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.

3.3.1 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 mentioned in section 3.1 that frequency channel allocation is a two-hop vertex coloring problem. The discussions in section 3.1 only represent ideal scenario. The two-hop vertex coloring problem is NP-complete and no efficient algorithm is known to date. Unless large number of frequencies are available, which is normally impractical, we can not guarantee that each node can be allocated a frequency channel that is different to all of its immediate neighbors.

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 [41]). A more efficient algorithm is still under design.

3.3.2 Broadcasting Traffic

One of the problems of using frequency division is how to deal with broadcasting traffic. Here we propose three approaches, each with its advantages and disadvantages.

In the first approach, each node transmits a broadcast packet to its neighbors with multiple unicasts. This approach is the most reliable approach because the resulted MAI is the same as normal unicast traffic. If each node has only a small number of neighbors and the broadcast traffic is not very high, this can be an acceptable approach. However, it may not be energy efficient because each packet has to be transmitted multiple times. The second approach is to employ a second transceiver[3]. 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. This approach is less reliable than the first one due to the MAI but is still better than the third one (see next). The network throughput may be degraded significantly when the broadcast traffic is high, but it is more energy efficient than the first approach because each broadcast packet is only transmitted once. The third approach also requires employment of 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). This approach has the worst reliability but is simple to implement. As RTS/CTS are normally not used for broadcast traffic, this approach should be adapted to a certain level of collisions. We are currently making a detailed comparison of these three schemes and will report the result in a future paper.

3.3.3 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 [19]. With proper coordination, nodes can sleep and wake up with the same duty cycle. Guo [22] *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.* [20] 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 [19]. 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.

4 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.

4.1 Simulation Setup

All simulations are conducted based on a randomly generated topology as shown in Figure 6, where 100 nodes are uniformly randomly deployed in a $100m \times 100m$ square area. We adopted a simple topology control protocol proposed in [5] 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

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

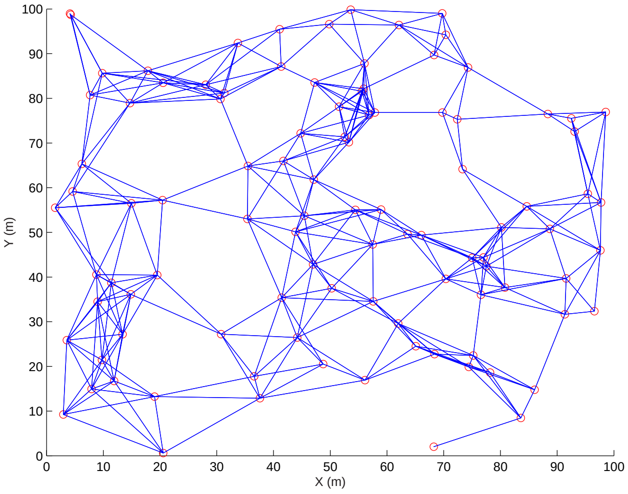

Figure 6: *Connection pattern of the random topology*

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 $\times$ 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:

$$\textit{MAI Threshold} = \frac{\sum_{i=1}^{k} P_i}{P_0} = 23.72 \tag{26}$$

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 [19], 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.

4.2 Simulation Results

From now onward, we refer our protocol as CDMA sensor MAC (CSMAC) [41] and m represents the number of frequency channels.

Table 1: 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	l
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

4.2.1 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 7 shows the packet drop rate comparison, where each point corresponds to 5 runs. We see that SMAC and CSMAC with $m = 1$ has 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 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.

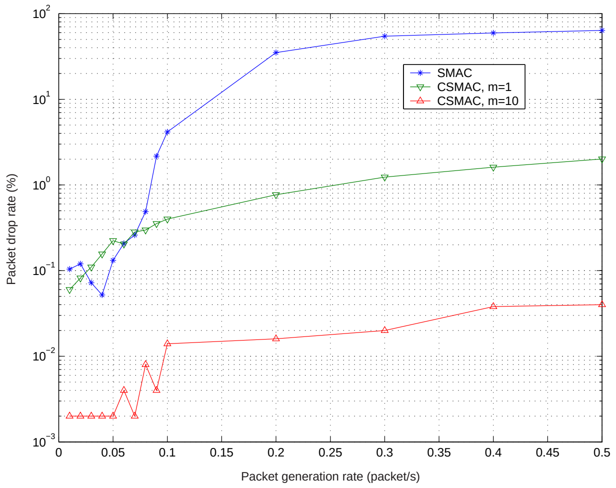

Figure 7: *Packet drop rate comparison with low traffic*

Figure 8 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

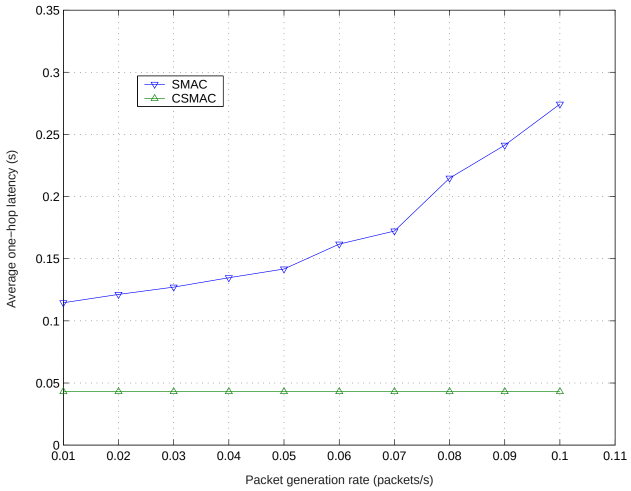

Figure 8: *Latency comparison*

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.

4.2.2 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 tracked as it may submerge the effect of communication energy consumption. Figure 9 shows the average energy consumption of each node with different number of frequencies and Table II gives the average energy consumption of each node. We see that CSMAC with

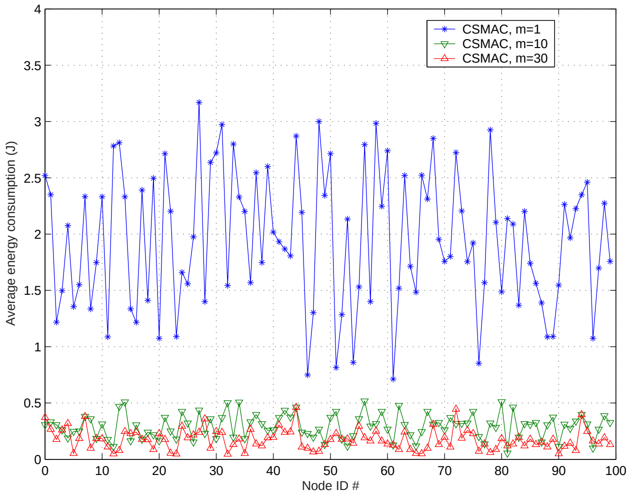

Figure 9: *Energy Consumption Comparison*

$m = 1$ consumes significant energy compared to $m = 10$ and $m = 30$ due to overhearing. By employing frequency division, CSMAC with $m = 10$ and $m = 30$ achieves 84% and 91% energy savings than $m = 1$. Figure 10 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 a small number of frequency channels. The energy savings become insignificant with further increases in number of frequencies.

Table 2: Average energy consumption per node

m	Average energy consumption (J)
1	1.9524
10	0.2938
30	0.1754

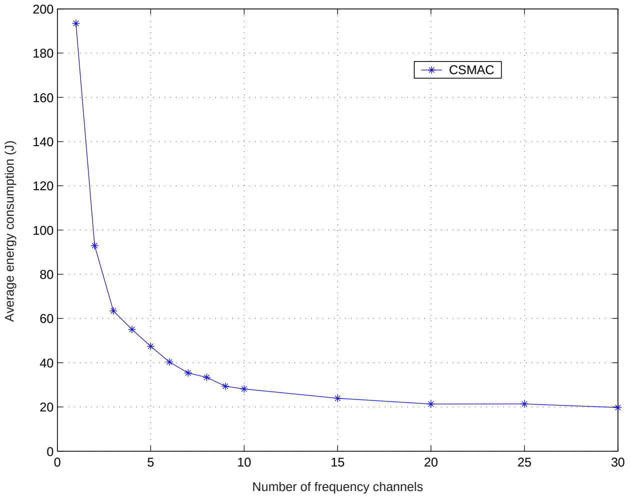

Figure 10: *Energy Consumption versus Number of Frequency Channels*

4.2.3 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, each node transmit to a different neighbor. The number of frequency channels used in this simulation include $m = 1$, $m = 5$, $m = 10$, and $m = 30$. Note that even $m = 30$ does not meet the requirement in equation 7. With node degree $\Delta = 9$ and according to equation 7, the minimum required frequency channels should be 72. However, we show that even with $m = 30$, our system achieves significant improvements. Figure 11 plotted the packet drop rate for all of the 5 different traffic patterns and their average performance. The first observation we make from Figure 11 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 2.2 that the limitation of using DS-CDMA in sensor network is due to the MAI and near-far effect. The second observation we make from Figure 11 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 show similar trend as our mathematical modeling in section 3.2, 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 11 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 3.2 and Figure 5.

One interesting thing that we can observe from Figure 11 is in scene 4 and scene 5, where $m = 5$ performs a little better than $m = 10$. This seems to be contradictory to our analysis above. The reason lies in that with a small number of frequency channels, the heuristic channel assignment protocol does not guarantee that each node and its neighbors can be assigned different frequency. If two (or more) nodes are accidently transmitting with the same frequency in the vicinity of interference range, the probability that the MAI threshold is

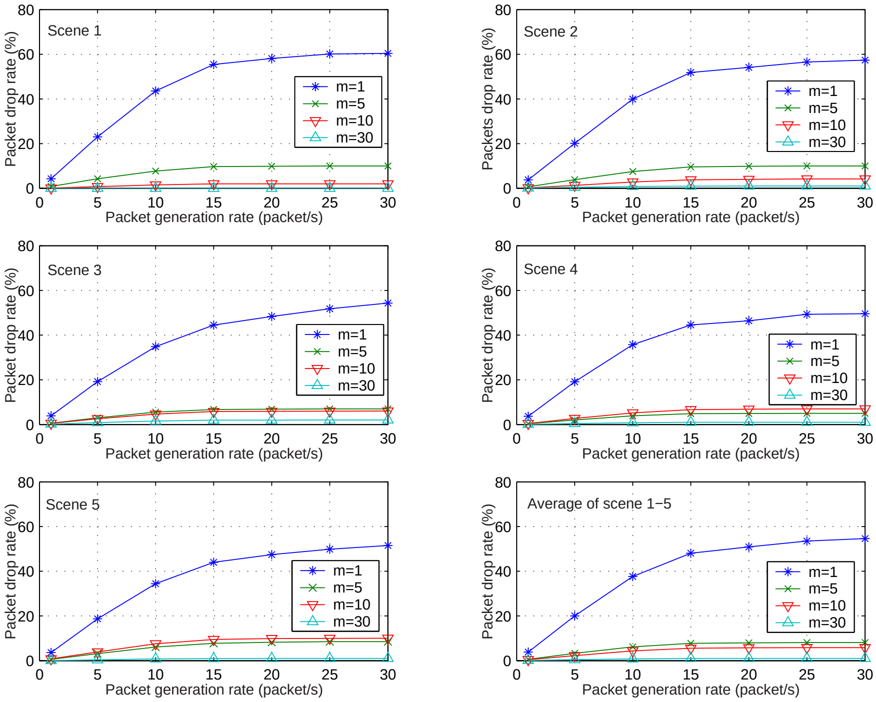

Figure 11: *Packet drop rate comparison with high traffic*

exceeded at a given node will be much higher, which leads to increases in the packet drop rate. This prompts us for one thing, with small number of frequency channels, a random channel assignment scheme may also be used as an alternative to heuristic scheme. Because even with heuristic scheme, we can not guarantee that the two-hop coloring criteria can be met. A random assignment scheme does not require a channel allocation protocol and is much easier to implement. Base on these analysis, we compare the performance between the heuristic and random channel assignment scheme.

4.2.4 Comparison between Heuristic and Random Channel Assignment Scheme

In this simulation, another 5 traffic patterns have been generated. The number of frequency channels are set to $m = 10$ and $m = 30$. Figure 12 shows the simulation results, where 'R' represents random and 'H' represents heuristic. We can see that on average, random assignment scheme indeed achieves reasonable packet drop rates. For example, even when the traffic is at 30 packet/s, which equals that all nodes are transmitting continuously, CSMAC with 'R, $m = 10$' achieves 4.25% drop rate and 'R, $m = 30$' achieves 2.75%. In the mean time, 'H, $m = 10$' achieves 2.5% drop rate which is similar to 'R, $m = 30$'. The performance of 'H, $m = 30$' is much better, the drop rate is only 0.37%. Interestingly, heuristic scheme with the same number of frequency channels sometimes performs even worse than the random scheme. For example, in scene 2 and scene 5, 'H, $m = 10$' performs worse than 'R, $m = 10$'. Another interesting thing is that 'R, $m = 10$' performs a little better than 'R, $m = 30$' in scene 4. The reason for these performance is due to the packet transmission pattern maintains the same in each run. The last average graph gives a better reflection on the performance comparison.

4.2.5 Summary

Our simulation results show that CSMAC with $m = 1$ can accommodate ten (e.g., from 0.1 packet/s to 1 packet/s) times higher traffic (Figure 7 and Figure 11) than a contention based protocol such as SMAC with similar acceptable packet drop rate (e.g., less than 5%). While CSMAC with $m = 30$ can accommodate another tens (e.g., from 1 packet/s to 30 packet/s) of times (Figure 11) higher traffic versus CSMAC with

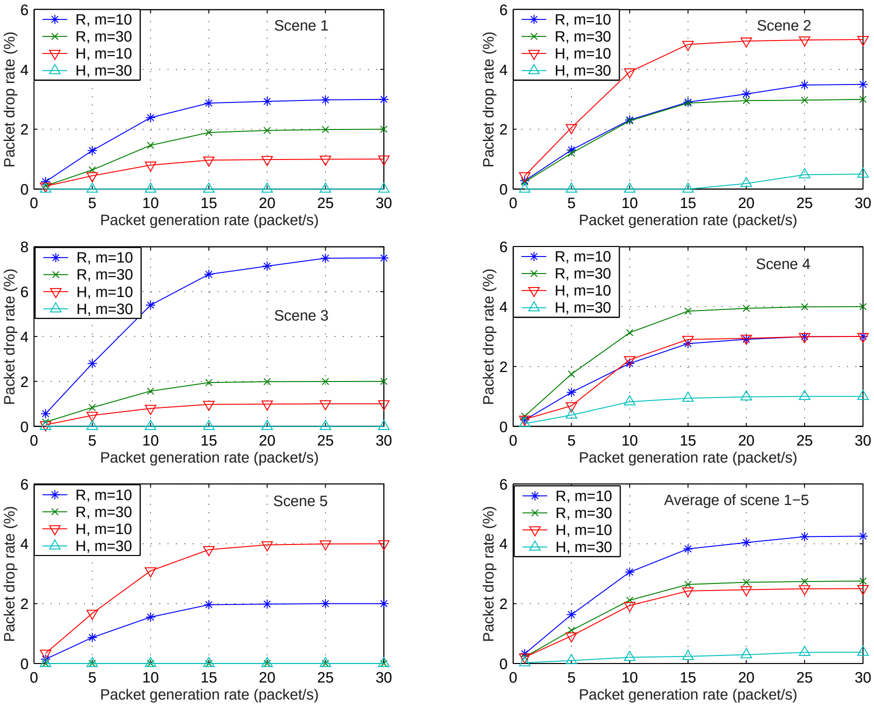

Figure 12: *Packet drop rate comparison between heuristic and random channel assignment*

$m = 1$ with very low packet drop rate. This is equivalent that a DS-CDMA system based on frequency division can accommodate several hundreds times network capacity than contention based protocols. Even random channel assignment scheme achieves a reasonable performance.

5 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 [6] 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. Dousse *et al.* studied the impact of interference on the connectivity of large-scale ad hoc networks using percolation theory. A TDMA-based channel access scheme, where each node emits during 1 slot for every n time slots, on the top of CDMA codes is proposed to address the interference-connectivity problem. Liu and Asada [9] proposed an energy efficient DS-CDMA system for sensor networks by using spreading code with more ‘0’ bits and employing on-off keying. Guo *et al.* [22] proposed a set of low power MAC design principles targeting at multi-hop wireless sensor networks. Sousa [10] *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.

Different MAC protocols have been proposed for sensor networks. SMACS[4] is a distributed protocol which enables a collection of nodes to discover their neighbors and establish transmission/reception schedules for communicating with them without the need for any local or global master nodes. Each node maintains a TDMA frame, called super frame, in which the node schedules different time slots to communicate with its known neighbors. Network formation in SMACS is not location-aware, so neighbors selected may not be nearest. Moreover, a node must wait its turn to transmit with TDMA approach even if the channel is idle. And this waiting time can accumulate along the multi-hop route from source to sink. Interestingly, SMACS also employed frequency division but assumes a TDMA and narrow band system.

Woo and Culler [14] propose a CSMA-based MAC protocol, designed specifically to support the periodic and highly correlated traffic of some sensor network applications. They propose an adaptive transmission rate control (ARC) scheme, whose main goal is to achieve media access fairness by balancing the rates of originating and route-through traffic. SMAC (Sensor-MAC) [19] is based on the IEEE 802.11 standard but improves upon its energy efficiency. SMAC identified several major sources of energy waste including *collision, overhearing, control packet overhead, and idle listening*. SMAC uses IEEE 802.11 CSMA/CA approach to avoid collision and puts a node to sleep when a neighbor node is transmitting to avoid overhearing. A scheduled periodic sleep and listening pattern is used to decrease the idle energy consumption. The main drawback of SMAC is high message delivery latency as SMAC is specially designed to sacrifice latency for energy savings.

6 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 3.3. Further development of our mathematical model for the network throughput and system capacity based on our current result is also under consideration. We would like to pursue these areas in our future research.

7 Acknowledgement

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