Adaptation of Multiple Access Parameters in Time Hopping UWB Cluster Based Wireless Sensor Networks

İsmail Güvenç and Hüseyin Arslan
Electrical Eng. Dept., Univ. of South Florida
4202 E. Fowler Ave., ENB-118, Tampa, FL, 33620
E-mail:{iguvenc,arslan}@eng.usf.edu

Sinan Gezici and Hisashi Kobayashi
Department of Electrical Engineering
Princeton University, Princeton, NJ 08544
E-mail: {sgezici,hisashi}@princeton.edu

Abstract

Ultrawideband (UWB) is an attractive physical layer technology for wireless sensor networks due to its unique characteristics. Flexibility in adjusting the processing gain of UWB systems makes it possible to tune the data rate and transmission range to fulfill the requirements of specific applications. Conventional systems assign identical multiple access parameters to all users regardless of the signal-to-interference plus noise ratio of the received signal. In this paper an adaptive assignment scheme for multiple access parameters in cluster based wireless sensor networks is investigated. First, an orthogonal time hopping sequence construction is proposed for synchronous communications (downlink), where the number of pulses per symbol are adjusted to meet the bit error rate requirement of an application. Then, adaptation of multiple access parameters in asynchronous scenarios (uplink) is evaluated using a Gaussian approximation method to model the multiple access interference in two cases: one with fixed frame duration, *where the goal is to increase the average throughput, and the other with* fixed symbol duration, *where the goal is to increase the network lifetime. Finally, a mathematical framework is developed for approximating the interference when the number of pulses per symbol and the frame duration vary.*

1 Introduction

Together with recent advances in integrated circuits, the evolution of wireless sensor networks (WSNs) towards inexpensive, low-power, and small-size implementations has gained incredible momentum. WSNs can be implemented in a variety of areas, such as military, telemedicine, telemetry, robotics, fault detection, consumer electronics, and security. Depending on the requirements of a specific application, the number of nodes in a WSN may range from a few nodes to thousands of nodes. In large WSNs, it is essential to have energy efficient communications to increase the network lifetime.

Ultrawideband impulse radio (UWB-IR) is a highly promising physical layer technology for WSNs due to its unique characteristics such as low power transmission, low cost and low complexity transceiver circuitry, unlicensed but masked spectrum availability, precise location capability, and secure transmission due to employed multiple access sequences. Time-hopping (TH) is a commonly used multiple access method for UWB-IR systems, besides the direct sequence (DS), and frequency hopping (FH) methods. By appropriately designing the TH codes, it is possible to control multiple access interference in UWB systems to a certain extent [14]. TH multiple access can provide interference free communications in synchronous systems. Even in an asynchronous system, excessive interference can be avoided due to low duty cycle and large processing gain of UWB-IR pulse transmission. Even if some of the pulses are corrupted, the rest of the pulses will be sufficient to extract the information. In addition, low complexity multiuser receivers, such as chip discriminators [18], can be used to discard the corrupted pulses, and implement adaptive rate control algorithms based on the interference level.

Adaptation of wireless communication systems allows better exploitation of the system resources based on the estimation of wireless link quality [2]. The link quality is often measured by the signal-to-interference plus noise ratio (SINR) of the received signal. For example, adaptive coding [6, 13] schemes can achieve higher throughput when the channel quality is good by decreasing the amount of redundancy transmitted. On the other hand, when the link quality is poor, reliable transmission can be insured by increasing the coding power (amount of redundancy). Similarly, adaptive modulation schemes can provide a range of modulation levels that can be implemented based on the channel quality [3]. For M-ary pulse position modulation (PPM), even though the data rate is increased by $\log_2 M$, increasing the modulation order M increases the effective time spanned by

0-7803-8815-1/04/$20.00 ©2004 IEEE

a single pulse by M. The good news is that the power efficiency is improved for higher order M-ary PPM schemes, i.e. less power is required to assure the same bit error rate (BER). On the other hand, higher order M-ary pulse amplitude modulation (PAM) levels have worse power efficiency (compared to lower order M-ary PAM schemes), but the data rate improves by $\log_2 M$ with the pulses spanning the same time duration. These characteristics of both higher order modulation schemes can be used to adapt to the changes in the link quality. Assigning multiple codes to the users, changing the pulse shape [22] and duration, and changing the transmitted pulse power [17] as in conventional schemes are other forms of adaptation in UWB systems to better exploit the system resources.

Adaptation of multiple access parameters in TH-UWB systems in terms of the number of pulses per symbol, and the frame duration is another flexible mean of exploiting system resources efficiently. Increasing the number of pulses per symbol increases the SINR, which can be considered as a power control approach in the time domain without changing pulse amplitudes. Increasing the frame duration (which is related with the cardinality of the code) again improves the SINR in a multiuser environment, as it becomes less likely that the pulses will receive hits. However, these improvements come in the expense of decrease in the data rate. By measuring the link quality (which is affected from the channel realization, multiuser interference etc.), it is possible to improve the data rate by modifying both parameters, while still ensuring a minimum BER (which is fixed by the quality of service (QoS) requirements). Alternatively, if the data rate is fixed by system requirements, when the link quality is good, the transmission power can be reduced to improve the network lifetime.

Adaptive rate and power allocation has been well studied for code division multiple access (CDMA) systems in the past [19, 16, 21, 4]. Optimal assignment of number of pulses per symbol and the frame duration for UWB systems in range limited and multiuser interference limited environments were analyzed in [8], where the Gaussian approximation is used to characterize the link quality and assess data rate gains for asynchronous communications. In [12], use of the standard Gaussian approximation (SGA) to capture the multiple access interference (MAI) in power unbalanced scenarios was investigated, and it was shown to be applicable to densely deployed networks. Another Gaussian approximation of MAI for chip synchronous and chip asynchronous scenarios was derived in [11] for a system with fixed number of pulses per symbol and fixed frame duration. Although adaptation of frame duration and number of pulses per symbol was analyzed in [20] in the context of medium access control (MAC) for UWB ad hoc networks, a mathematical framework for the MAI has not been developed. In [7, 23], radio resource allocation problem was analyzed as a theoretical constraint optimization problem for ad hoc networks, where the system throughput is maximized considering UWB physical layer, traffic patterns, and system topology. Both reserved bandwidth (QoS) and dynamic bandwidth (best effort) scenarios are considered, and admission policies of new users to the system are presented.

In this paper, adaptation of multiple access parameters both in synchronous and asynchronous communication is investigated for cluster based WSNs, and theoretical performance analysis to characterize the link quality is presented for different scenarios. For synchronous communications (downlink), an orthogonal TH sequence construction approach is proposed, which resembles orthogonal variable spreading factor (OVSF) codes in CDMA systems. For asynchronous communications, multiuser interference is modelled with a Gaussian approximation approach for two communication scenarios: *fixed frame duration*, where the goal is to maximize the overall data rate, and *fixed symbol duration*, where the goal is to have an identical data rate for all the users, and improve the network lifetime. For the fixed symbol duration case, the required symbol energy to meet the BER requirement is calculated, and the number of pulses to be employed in transmission is evaluated (which implies joint assignment of both the number of pulses per symbol and the frame duration, as the symbol duration is constant). Improvements in the data rate and power consumption for both schemes are demonstrated with computer simulations for fixed and mobile cluster head cases.

2 System Model

2.1 UWB Signal Model

In this section, a generic UWB signal model is introduced, where a variable number of pulses per symbol, as well as variable frame durations are allowed for different users. The transmitted UWB signal from user k in an N_u user system is given by

$$s_k(t) = \sqrt{E_{tp}^{(k)}} \sum_{j=-\infty}^{\infty} a_j^{(k)} b_{\lfloor j/N_s^{(k)} \rfloor}^{(k)} \omega_{tx}(t - jT_f^{(k)} - c_j^{(k)} T_c), \tag{1}$$

where $T_f^{(k)}$ is the frame duration of user k, j is the frame index, T_c is the chip duration, $E_{tp}^{(k)}$ is the transmitted pulse energy of user k, and ω_{tx} represents the transmitted pulse shape with unit energy. The number of frames per information bit for user k is denoted as $N_s^{(k)} = T_s^{(k)}/T_f^{(k)}$, where $T_s^{(k)}$ is the symbol period for user k, and number of chips per frame of user k is denoted by $N_h^{(k)}$. The random polarity codes $a_j^{(k)}$ are binary random variables taking values

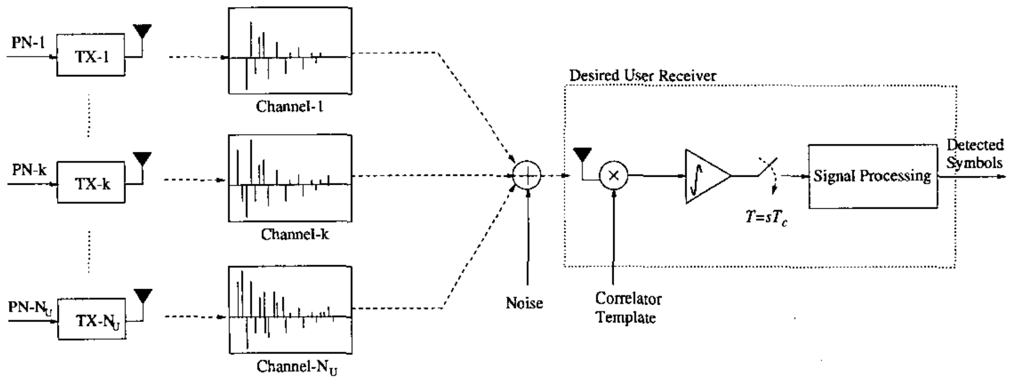

Figure 1. The received signals from multiple users and the correlator receiver.

± 1 with equal probability, and $a_j^{(k)}$ and $a_i^{(l)}$ are independent for $(k,j) \neq (l,i)$ [9]. Also, $c_j^{(k)} \in \{0,1,...,N_c-1\}$ with equal probability, and $c_j^{(k)}$ and $c_i^{(l)}$ are independent for $(k,j) \neq (l,i)$. The transmitted bits of user k are denoted by $b^{(k)}_{\lfloor j/N_s^{(k)} \rfloor} \in \{-1,+1\}$.

The received signal is expressed as

$$r(t) = \sum_{k=1}^{N_u} \sqrt{E_{rp}^{(k)}} \sum_{j=-\infty}^{\infty} a_j^{(k)} b^{(k)}_{\lfloor j/N_s^{(k)} \rfloor} \omega_{rx}(t - jT_f^{(k)} - c_j^{(k)} T_c - \tau_k) + \sigma_n n(t), \quad (2)$$

where $E_{rp}^{(k)}$ is the received pulse energy, τ_k is the delay of user k, ω_{rx} denotes the received UWB pulse, $n(t)$ is a zero mean white Gaussian noise process with unit spectral density, and σ_n denotes the standard deviation of the noise before the matched filter (MF).

Consider a MF receiver (see Fig. 1) with the following template signal for the zeroth bit of user ξ ($b_0^{(\xi)}$), without loss of generality:

$$s_{temp}^{(\xi)}(t) = \sum_{j=0}^{N_s^{(\xi)}-1} a_j^{(\xi)} \omega_{rx}(t - jT_f^{(\xi)} - c_j^{(\xi)} T_c - \tau_\xi). \quad (3)$$

Then, the output of the MF is given by

$$Y = \sqrt{E_{rp}^{(\xi)}} b_0^{(\xi)} N_s^{(\xi)} + M + N, \quad (4)$$

where $N \sim \mathcal{N}(0\,,\, N_s^{(\xi)} \sigma_n^2)$ is the output noise and M is the total MAI, which is the sum of interference terms from the interfering users

$$M = \sum_{k=1, k\neq\xi}^{N_u} M_k, \quad (5)$$

where M_k is the MAI from user k. The statistics of M will be analyzed in Section 3.2.

2.2 Sensor Network Model and BER Evaluation

In this paper, a cluster based WSN is analyzed, where the cluster head has more complex circuitry, and therefore higher processing capabilities compared to the sensor nodes. Note that from robustness, self configurability, and an overall network lifetime perspective it is more appropriate that each node can have the capability to be the cluster head. However, this increases the overall cost of the nodes, as being a cluster head has considerably larger complexity, and in particular for UWB systems, requires a separate correlator for each sensor. Therefore, the former approach is taken for the rest of the paper. The communication happens in rounds as in [15], where, after each round, the cluster head may update the multiple access parameters. Consider a cluster of N_u sensors, with each node having a transmitted pulse energy of $E_{tp}^{(k)}$ to communicate with the cluster head, which transmits the information to a remote base station. The received pulse energy for user k at the cluster head is given by

$$E_{rp}^{(k)} = E_{tp}^{(k)} \frac{\alpha_k}{d_k^n} \quad (6)$$

where n denotes the path loss exponent, d_k is the distance between the kth sensor node and the cluster head, and α_k is the fading coefficient for user k. When there is no MAI, the probability of error for user k which employs binary phase shift keying (BPSK) modulation is given by

$$P_b^{(k)} = Q\left(\sqrt{\mathrm{SNR}_k}\right) = Q\left(\sqrt{\frac{N_s^{(k)} E_{rp}^{(k)}}{\sigma_n^2}}\right), \quad (7)$$

Table 1. Code construction algorithm

for $k = 1 : N_u$
  $\mathbf{c^k} = \text{rand}(\mathbf{S}, N_s^{(k)})$
  $\mathbf{S} = \mathbf{S} - \mathbf{c^k}$
end

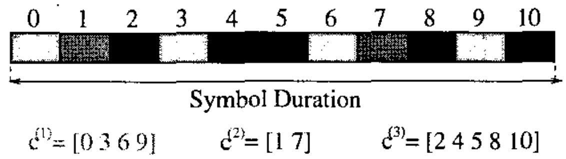

Figure 2. An example code construction for three users with different processing gains.

where, energy per symbol (bit) of user k is given by $E_{rs}^{(k)} = N_s^{(k)} E_{rp}^{(k)}$, $Q(x)$ is given by $\frac{1}{2}\text{erfc}(\frac{x}{\sqrt{2}})$, and SNR denotes the signal-to-noise ratio (interference effects will be considered later). Conventional UWB networks use the same number of pulses per symbol, and the same frame duration for each user, ensuring reliable communication with the furthest away user. If the minimum BER required by the system is given by P_b, the processing gain assigned to each user is given by

$$N_s = \frac{\left[Q^{-1}(P_b)\right]^2 \sigma_n^2}{E_{rp}^{min}} . \quad (8)$$

where E_{rp}^{min} denotes the minimum received pulse energy, which is from the furthest away user in an ideal environment. The raw data rate for each user is then given by $\frac{1}{N_s N_h T_c}$.

3 Adaptation of Multiple Access Parameters

In order to better exploit the system resources, it is possible to change the number of pulses ($N_s^{(k)}$), and number of chips per frame ($N_h^{(k)}$), for each user based on the channel quality, the distance of the user from the cluster head, the long and short term fading effects, and the interference level in the system. In this section, first, synchronous communications will be considered, where the orthogonal construction of TH sequences allows interference-free communication, such as in the downlink. Then, adaptation of $N_s^{(k)}$ and $N_h^{(k)}$ in asynchronous systems is analyzed under a BER constraint and for two different cases: fixed frame duration (to maximize the data rate), and fixed symbol duration (to maximize the network lifetime).

3.1 Synchronous Communications

In synchronous communications, it is possible to design the TH codes orthogonally to avoid MAI. In this mode of operation, the cluster head may assign just enough number of pulses to each sensor node k to ensure the desired BER P_b

$$N_s^{(k)} = \left\lceil \frac{\left[Q^{-1}(P_b)\right]^2 d_k^n \sigma_n^2}{E_{tp}^{(k)} \alpha^k} \right\rceil , \quad (9)$$

where $\lceil x \rceil$ is the smallest integer greater than or equal to x. The orthogonal construction of the codes with different processing gains is carried out as follows. Let N_c denote the number of chip positions within the symbol period. After each round, each sensor can report the observed SNR, and using (9), cluster head can evaluate N_c prior to constructing new set of time hopping codes as follows

$$N_c = \sum_{k=1}^{N_u} N_s^{(k)} . \quad (10)$$

Note that N_c is a just enough number of chips per symbol, and determines the data rate common to all sensor nodes. In addition to changes in the channel quality, due to movements/deaths of the nodes or a movement of the cluster head, the distances may change, which may change the value of N_c after each round. After calculating N_c, the cluster head constructs the orthogonal codes as given in Table 1, where S is the set of integers ranging from 1 to N_c, rand(S, $N_s^{(k)}$) denotes $N_s^{(k)}$ random integers chosen from set S, and the operator "$-$" excludes the set of numbers on the right of the operator from the set on the left of the operator[1]. In Fig. 2, a simple example for the downlink TH sequences of 3 users employing different processing gains is presented. In a sense, the proposed construction is similar to OVSF codes in CDMA systems, however, our construction is more flexible, as the length of a particular code does not need to be a multiple of the length of any of the shorter length codes. For the sake of simplicity, the codes are constructed in a random manner, which works well for single tap (flat fading) channels. For dispersive channels, more sophisticated code designs can be used [14], where a

[1] Note that conventional frame-based code and signal notation in (2) is not used here, where the sequence $\mathbf{c^k}$ for user k points to the locations of the pulses within the symbol, rather than within the frame (i.e. there are no frames, and the common symbol duration is $N_C T_C$).

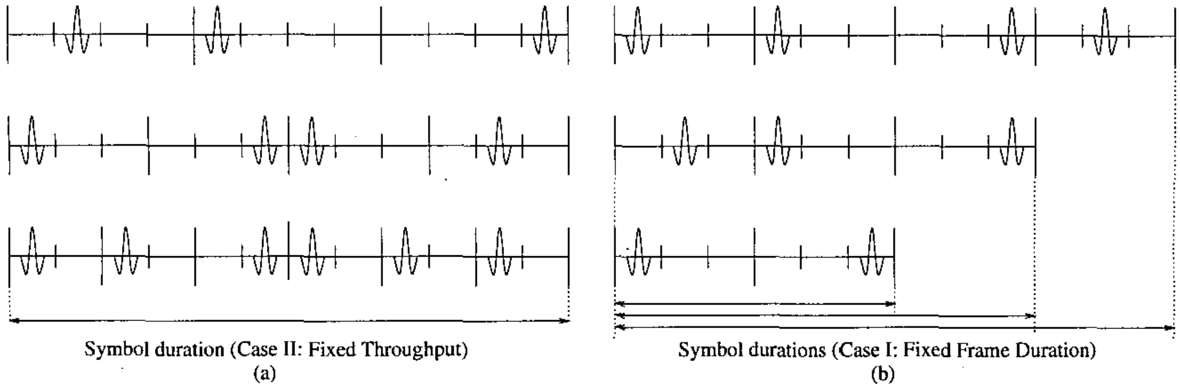

Figure 3. Example transmitted signals for a) Fixed throughput , and b) Fixed frame duration.

larger pulse duration may be presumed to compansate for the channel effects.

The average data rate with the proposed scheme will improve since the average number of pulses per symbol decreases, and is given by $\frac{1}{N_c T_s}$. On the other hand, the total transmitted power for any round is fixed for all cases, and individual user powers are adapted indirectly through changing number of pulses per symbol. The proposed method also improves the energy consumption (per symbol), as less aggregate energy will be used per symbol.

3.2 Asynchronous Communications

In the previous section, it is assumed that the UWB system is completely synchronized. This requires compensation of delays in various multipath arrivals, which is not generally feasible in the uplink, but may be considered for downlink communications. Therefore, uplink transmission is usually assumed to be asynchronous, and multiple access interference degrades the system performance. For analytical purposes, we approximate an asynchronous UWB system by a chip-synchronous system, where the misalignment between the symbols of the users are integer multiples of the chip interval T_c. Assuming without loss of generality that the delay of the desired user is zero ($\tau_d = 0$), we assume that $\tau_k = \Delta_k T_c$ for $k \neq d$, where $\Delta_k \in \{0, 1, \ldots, N_h^{(k)} N_s^{(k)} - 1\}$ with equal probability. As studied in [11], the chip-synchronous assumption usually results in over-estimating the error probability, and hence the system design based on this approximation will be on the safe side.

In order to calculate the BER of the desired user in the presence of multiple users with random time hopping codes, we will employ Gaussian approximations for large number of pulses per information symbol. This is similar to the Gaussian approximations employed in [9] and [11]. However, we derive a more general formula in the case of different number of pulses per symbol in the fixed throughput case below. Later in this section, fixed frame duration and fixed symbol duration cases are analyzed seperately.

3.2.1 Case 1: Fixed Frame Duration

In this case, the frame durations of all the users are the same. Hence, N_h is common for all of them (see for example Fig. 3b, where $N_s^{(1)} = 4$, $N_s^{(2)} = 3$, $N_s^{(3)} = 2$, and $N_h^{(k)} = 3$ for all k). The aim is to meet the BER requirement for all users in the system.

In order to satisfy a certain BER threshold, we adapt the number of pulses per symbol so that we can maximize the overall data rate of the system [8].

Similar to the approach in [11], we can approximate the MAI from user k by the following Gaussian random variable, when the number of pulses per information symbol for user ξ, $N_s^{(\xi)}$, is large:

$$M_k \sim \mathcal{N}\left(0, E_{rp}^{(k)} \frac{N_s^{(\xi)}}{N_h}\right), \tag{11}$$

where $E_{rp}^{(k)}$ is the energy of a received pulse from user k.

Then, we can express, using (4) and (5), the SINR of the system for user ξ as

$$\text{SINR} = \frac{(N_s^{(\xi)})^2 E_{rp}^{(\xi)}}{N_s^{(\xi)} \sigma_n^2 + \frac{N_s^{(\xi)}}{N_h} \sum_{\substack{k=1 \\ k \neq \xi}}^{N_u} E_{rp}^{(k)}}, \tag{12}$$

from which the value of $N_s^{(\xi)}$ can be obtained as

$$N_s^{(\xi)} = \left\lceil \frac{\text{SINR}}{E_{rp}^{(\xi)}} \left(\sigma_n^2 + \frac{1}{N_h} \sum_{\substack{k=1 \\ k \neq \xi}}^{N_u} E_{rp}^{(k)} \right) \right\rceil . \quad (13)$$

In other words, by setting the value of $N_s^{(\xi)}$ according to (13), we transmit just enough number of pulses per symbol to meet the BER requirement. This is contrary to conventional systems, where the worst case parameters are used for all users, hence a lower overall data rate is obtained. Note that all the users transmit with the same power over a block, however, for a given transmitted power, the bit rate will depend on the link quality.

3.2.2 Case 2: Fixed Throughput

Now consider the case where a fixed throughput is to be assigned to all users. Hence, we consider a common symbol time and BER in this scenario. In other words, the total processing gain defined by $N_c = N_s^{(k)} N_h^{(k)}$ is constant in this case (see Fig. 3a, where $(N_s^{(1)}, N_h^{(1)}) = (3,4)$, $(N_s^{(2)}, N_h^{(2)}) = (4,3)$, and $(N_s^{(3)}, N_h^{(3)}) = (6,2)$). Therefore, we can change the number of pulses per symbol and the frame duration as long as their multiplication is fixed. In this case, we employ the following lemma to approximate the MAI from user k:

Lemma 1: *In a chip-synchronous scenario, the distribution of the MAI from user k converges to the following Gaussian random variable*

$$M_k \sim \mathcal{N}\left(0, E_{rp}^{(k)} \frac{N_s^{(\xi)}}{N_h^{(k)}}\right), \quad (14)$$

as $\min\{N_s^{(\xi)}, N_s^{(k)}\} \longrightarrow \infty$.

Proof: *See Appendix A.1.*

Hence, the total MAI can be approximated as

$$M \sim \mathcal{N}\left(0, N_s^{(\xi)} \sum_{k=1, k\neq\xi}^{N_u} \frac{E_{rp}^{(k)}}{N_h^{(k)}}\right). \quad (15)$$

Then, the SINR of the system can be obtained as

$$\text{SINR} = \frac{(N_s^{(\xi)})^2 E_{rp}^{(\xi)}}{N_s^{(\xi)} \sigma_n^2 + N_s^{(\xi)} \sum_{\substack{k=1 \\ k\neq\xi}}^{N_u} \frac{E_{rp}^{(k)}}{N_h^{(k)}}}, \quad (16)$$

which can be expressed as

$$\text{SINR} = \frac{E_{rs}^{(\xi)}}{\sigma_n^2 + \frac{1}{N_c} \sum_{\substack{k=1 \\ k\neq\xi}}^{N_u} E_{rs}^{(k)}}, \quad (17)$$

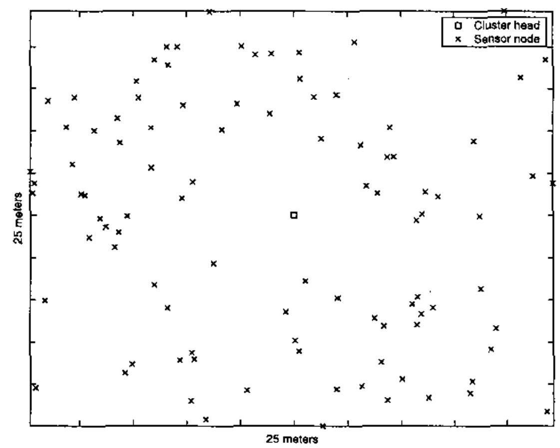

Figure 4. A realization of sensor distribution over the geographical area.

by the defining the received *symbol* energy of the kth user by $E_{rs}^{(k)} = N_s^{(k)} E_{rp}^{(k)}$ for $k = 1, \ldots, N_u$.

When we assign the same SINR values to all the users, they have the same BER, hence the same throughput since they have the same symbol time. Hence, from (17), we see that we can choose the same received symbol energy to achieve the same BER for all users. Denoting that common energy by E_{rs}, we obtain from (17) that

$$E_{rs} = \frac{\sigma_n^2 \,\text{SINR}}{1 - \left(\frac{N_u - 1}{N_c}\right) \text{SINR}}. \quad (18)$$

In other words, for a desired SINR value, we can calculate the required received symbol energy of the users. Note that the received symbol energy can be expressed as

$$E_{rs} = E_{ts}^{(k)} \frac{\alpha_k}{d_k^n}. \quad (19)$$

Since the symbol energy is the multiplication of the number of pulses per symbol and the pulse energy, we get

$$E_{rs} = N_s^{(k)} E_{tp}^{(k)} \frac{\alpha_k}{d_k^n}. \quad (20)$$

Note that the users can use different number of pulses per symbol and/or different pulse energy depending on the channel state and their location. In a practical setting, the cluster head can calculate the SINR for each user and feedback them how to scale their symbol energy in order to achieve the desired SINR.

Note that when a user is very far away from the cluster head or its channel is in a deep fade, the transmitted symbol energy needs to be increased considerably, which might

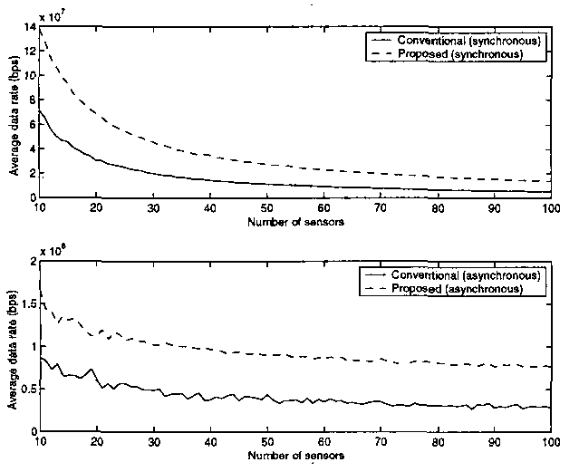

Figure 5. Data rate improvements using the adaptive approach in synchronous and asynchronous scenarios.

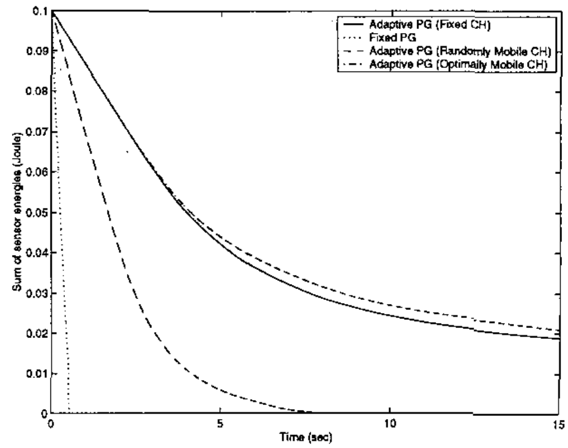

Figure 6. Remaining aggregate energy in the network.

violate the FCC's regulations [1]. Therefore, multi-hopping might be necessary in some cases.

Finally, it is observed that given the fading coefficient and distance of user k, the energy can be set by changing $N_s^{(k)}$ and/or $E_{tp}^{(k)}$. In other words, there is a flexibility in adjusting the symbol energy. However, there are a few issues to consider when setting the symbol energy. First, the FCC's restriction on the peak-to-average signal ratio can restrict the use of very small $N_s^{(k)}$ values. Secondly, although we consider flat fading channels in this paper, the inter-frame interference (IFI) can be an issue in a multipath environment when choosing the number of frames per symbol, where choosing larger frames reduces the effects of the IFI.

3.3 Extension to Multipath Channels

Although the previous analysis assumes AWGN channels, extention to multipath channels is also possible. In that case, we consider RAKE receivers since a MF would not gather sufficient signal energy due to large delay spread of UWB channels. By similar approaches to the one in [10], it can be shown that the MAI from an interfering user converges to zero mean Gaussian random variables similar to the ones in (11) and (14), with the only difference being a scaling factor to the variance terms. That scaling factor purely depends on the multipath channel of the interfering user and the finger assignment of the RAKE receiver. In other words, the same dependence on the received pulse energy and the processing gain parameters (N_s and N_h) is preserved. Due to space limitations, extensive analysis of the MAI in adaptive IR-UWB systems over frequency-selective channels is not included in this study.

4 Simulation Results

Computer simulations are performed to demonstrate the improvements in the data rate and power consumption. Single cluster of a WSN is considered, and 100 sensor nodes are randomly distributed over the field (25×25 meters as in Fig. 4). An SNR of 8.39dB is targeted, which corresponds to a BER of 10^{-4} for BPSK modulation, path loss exponent is taken as $n = 2.4$, pulse width is set to $T_c = 0.3$ns, and chip synchronous case is taken in all scenarios. It is assumed that the transmitted pulse occupies the whole 7.5GHz of bandwidth in between 3.1GHz − 10.6GHz, and knowing that the FCC mask allows a maximum transmission power of −41dBm/MHz within this frequency range, maximum transmitted energy per second can be calculated as 0.562mW. This is the maximum power that any sensor can transmit to comply with FCC regulations, and may restrict choosing optimum N_h and N_s even if SINR is appropriate.

For synchronous communications, data rate improvement with respect to number of users is evaluated when optimum $N_s^{(k)}$ are used to construct orthogonal sequences for each user (equations (8) and (9)), and averaged over 100 realizations of the sensor distributions. Noise variance is taken to be 20dB weaker than the energy per transmitted pulse. Two schemes are analyzed: conventional approach, where the worst case processing gain are used for all the

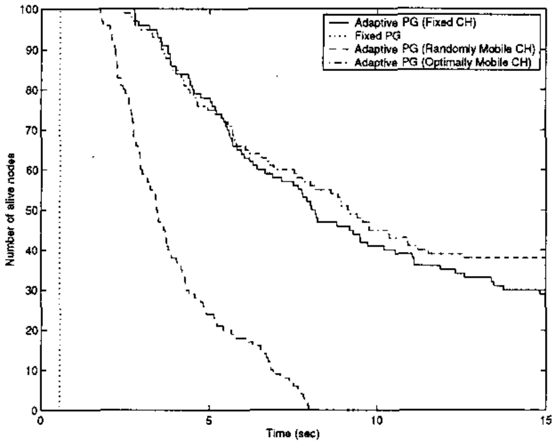

Figure 7. Number of alive nodes in the network.

users; and the adaptive approach, where just enough processing gain is assigned to each user. Results in first part of Fig. 5 show that the average data rate for synchronous communications with the proposed method is at least twice the conventional approach. Note that Fig. 5 does not demonstrate the gains obtained due to deaths and mobilities of the sensors, which are exploited periodically to update the codes and increase the data rate. Furthermore, a trivial analysis can be repeated to demonstrate the additional savings in power consumption due to the decrease in the average processing gain used per symbol.

For asynchronous communications, *case 1* and *case 2* are analyzed separately. For case 1, Gaussian approximation is used to evaluate the data rates for conventional and proposed methods in an interference limited environment. Simulation results in second part of Fig. 5 imply that increasing the number of sensors does not effect the data rate significantly as it affects the synchronous communications. This is because a fixed frame duration is used for different number of users, and the number of pulses per symbol is the only term that determines the data rate. In the conventional method, the data rate is lower-bounded by the data rate of the furthest away user, which does not change significantly with the number of users. For adaptive implementation, since fewer pulses are used for closer sensors, higher aggregate data rates are achieved.

Simulation results for *case 2* are presented in Figs. 6 and 7, where the data rates are identical for all the users and is set to $(N_cT_c)^{-1} = (10^4 \times 0.3 \times 10^{-9})^{-1} =$ 33kbps. Continuous transmission of all the sensors, and very low initial battery energy assignments (1mJ) for each node are assumed for simulation purposes. The parameters are updated after each round of 300μsec to adapt to Rayleigh fading channel and possibly changed distances, and energy consumption in 5×10^4 rounds is analyzed. Simulation results show substantial gains in network lifetime when using adaptive assignment of processing gain (PG). Also, the effects of mobility of the cluster head (CH) is analyzed, which may be considered for example for rescue-robot applications where the robot acts as a cluster head to communicate with various sensors, and although the power consumption of the robot is not that important, we would like to maximize the network lifetime of the sensors. It is observed in Figs. 6 and 7 that if the cluster head randomly moves in the network, the network lifetime shortens seriouslt. On the other hand, movement of the cluster head after each round to an optimal location (which is the expected value of the locations of the *alive* sensor nodes, i.e. $E[x_s, y_s]$, where (x_s, y_s) are the coordinates of each sensor node) slightly increases the network lifetime compared to the case when the cluster head is motionless and located at the center of the network.

5 Conclusion

In this paper, adaptation of multiple access parameters in cluster based UWB-IR WSNs has been analyzed for both synchronous and asynchronous communication scenarios. For synchronous communications, an orthogonal sequence construction has been presented, which assigns variable processing gains to the sensors, and acquires the desired BER requirement at each sensor. For asynchronous communication systems, Gaussian approximation methods have been used to adapt the transmission powers and processing gains of the sensors, and a mathematical framework has been developed for the analysis of MAI when the number of pulses per symbol and frame duration of each user are different. Data rate and power savings improvements have been demonstrated using computer simulations.

References

[1] Federal Communications Commision: Revision of part 15 of the commision's rules regarding ultra-wideband transmission system, April 2002.

[2] H. Arslan. *Adaptation Techniques and the Enabling Parameter Estimation Algorithms for Wireless Communication Systems.* Book Chapter, Signal Processing Communications Handbook, CRC Press, 2004.

[3] N. J. August, R. Thirugnanam, and D. S. Ha. An adaptive UWB modulation scheme for optimization of energy, BER, and data rate. In *Proc. IEEE Ultrawideband Systems Technol. (UWBST)*, Kyoto, Japan, May 2004.

[4] F. Berggren and S. L. Kim. Energy-efficient control of rate and power in DS-CDMA systems. *IEEE Trans. Wireless Commun.*, 3(3):725–733, May 2004.

[5] P. Billingsley. *Probability and Measure*. John Wiley & Sons, New York, 2nd edition, 1986.

[6] J. Y. L. Boudec, R. Merz, B. Radunovic, and J. Widmer. A MAC protocol for UWB very low power mobile ad-hoc networks based on dynamic channel coding with interference mitigation. Technical report, EPFL Technical Report ID: IC/2004/02, Lausanne, Switzerland, Jan. 2004.

[7] F. Cuomo, C. Martello, A. Baiocchi, and F. Capriotti. Radio resource sharing for ad hoc networking with UWB. *IEEE J. Select. Areas Commun.*, 20(9):1722–1732, Dec. 2002.

[8] J. Diaz and Y. Bar-ness. Adaptive transmission for UWB impulse radio communications. In *Proc. Conf. on Information Sciences Syst. (CISS)*, Baltimore, MD, Mar. 2003.

[9] E. Fishler and H. V. Poor. On the tradeoff between two types of processing gain. In *Proc. 40th Annual Allerton Conf. on Commun. Control Computing*, Monticello, IL, Oct. 2002.

[10] S. Gezici, H. Kobayashi, H. V. Poor, and A. F. Molisch. Performance evaluation of impulse radio UWB systems with pulse-based polarity randomization. *Submitted to IEEE Trans. Sig. Processing, Nov. 2003; Revised May 2004.*

[11] S. Gezici, H. Kobayashi, H. V. Poor, and A. F. Molisch. Performance evaluation of impulse radio UWB systems with pulse-based polarity randomization in asynchronous multiuser environments. In *Proc. IEEE Wireless Commun. Networking Conf. (WCNC)*, Atlanta, GA, Mar. 2004.

[12] G. Giancola, L. D. Nardis, and M. G. D. Benedetto. Multi user interference in power-unbalanced ultra wide band systems: Analysis and verification. In *Proc. IEEE Ultrawideband Syst. Technol. Conf. UWBST*, pages 325–329, Reston, VA, Nov. 2003.

[13] G. Giancola, L. D. Nardis, M. G. D. Benedetto, and E. Dubuis. Dynamic resource allocation in time varying ultra wideband channels. In *Proc. IEEE Int. Conf. Commun. (ICC)*, Paris, France, June 2004.

[14] I. Guvenc and H. Arslan. Design and performance analysis of time hopping sequences for UWB-IR systems. In *Proc. IEEE Wireless Commun. Networking Conf. (WCNC)*, volume 2, pages 914–919, Atlanta, GA, Mar. 2004.

[15] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan. Energy efficient communication protocol for wireless microsensor networks. In *Proc. Annual Hawai International Conferance on System Sciences*, pages 3005–3013, Hawai, Jan. 2000.

[16] D. Kim. Rate-regulated power control for supporting flexible transmission in future CDMA mobile networks. *IEEE J. Select. Areas Commun.*, 17(5):968–977, May 1999.

[17] S. S. Kolenchery, J. K. Townsend, J. A. Freebersyser, and G. Bilbro. Performance of local power control in peer-to-peer impulse radio networks with bursty traffic. In *Proc. IEEE Global Telecommun. Conf.*, volume 2, pages 910–916, Phoenix, AR, Nov. 1997.

[18] W. M. Lovelace and J. K. Townsend. Adaptive rate control with chip discrimination in UWB networks. In *Proc. IEEE Ultrawideband Systems Technol. (UWBST)*, pages 195–199, Reston, VA, Nov. 2003.

[19] S. J. Oh and K. M. Wasserman. Adaptive resource allocation in power constrained cdma mobile networks. In *Proc. IEEE Wireless Commun. Networking Conf. (WCNC)*, volume 1, pages 510–514, New Orleans, LA, Sept. 1999.

[20] H. Yomo, P. Popovski, C. Wijting, I. Z. Kovacs, N. Deblauwe, A. F. Baena, and R. Prasad. Medium access techniques in ultra-wideband ad hoc networks. In *Proc. 6th National Conf. of Society for Electronic, Telecommun., Automatics, and Informatics (ETAI)*, Ohrid, Macedonia, Sep. 2003.

[21] L. C. Yun and D. G. Messerschmitt. Variable quality of service in CDMA systems by statistical power control. In *Proc. IEEE Int. Conf. Commun.*, volume 2, pages 713–719, June 1995.

[22] H. Zhang and R. Kohno. Soft-spectrum adaptation in UWB impulse radio. In *Proc. IEEE Personal Indoor Mobile Radio Commun. (PIMRC)*, volume 1, pages 289–293, Beijing, China, Sep. 2003.

[23] H. Zu and A. Ganz. A radio resource control method in UWB MAC protocol design. In *Proc. IEEE Military Commun. Conf. (MILCOM)*, volume 2, pages 886–891, Boston, MA, Oct. 2003.

A Appendices

A.1 Proof of Lemma 1

Using (2) and (3), the MAI from user k, M_k in (5), can be expressed as follows

$$M_k = \sqrt{E_{rp}^{(k)}} \sum_{l=0}^{N_s^{(\xi)}-1} M_{k,l}, \quad (21)$$

where

$$M_{k,l} = a_l^{(\xi)} \sum_{j=-\infty}^{\infty} a_j^{(k)} b_{\lfloor j/N_s^{(k)} \rfloor}^{(k)} R(jT_f^{(k)} - lT_f^{(\xi)} + c_j^{(k)}T_c - c_l^{(\xi)}T_c - \Delta_k T_c), \quad (22)$$

with $\Delta_k = (\tau_k - \tau_\xi)/T_c$ being the amount of asynchronism between the desired user and user k in terms of the chip interval.

Assume that $N_s^{(\xi)} \leq N_s^{(k)}$. In this case, it can be shown that $\{M_{k,l}\}_{l=0}^{N_s^{(1)}-1}$ form a 1-dependent sequence [5], where each term is zero mean due to the random polarity codes ($\mathrm{E}\{M_{k,l}\} = 0$). Hence, as $N_s^{(\xi)} \longrightarrow \infty$, $\frac{1}{\sqrt{N_s^{(1)}}} \sum_{l=0}^{N_s^{(1)}-1} M_{k,l}$ converges to $\mathcal{N}(0\,, \mathrm{E}\{M_{k,l}^2\} + 2\mathrm{E}\{M_{k,l}M_{k,l+1}\})$ [5].

It can be shown that the correlation terms are zero due to the fact that random polarity codes are zero mean and independent for different indices. Also after some manipulation, we obtain $\mathrm{E}\{M_{k,l}^2\} = 1/N_h^{(k)}$. Hence, we get

$$\frac{1}{\sqrt{N_s^{(\xi)}}} \sum_{l=0}^{N_s^{(\xi)}-1} M_{k,l} \sim \mathcal{N}\left(0\,,\frac{1}{N_h^{(k)}}\right), \qquad (23)$$

as $N_s^{(\xi)} \longrightarrow \infty$.

Therefore, for large $N_s^{(\xi)}$, we can approximate M_k in (21) as in (14).

For $N_s^{(\xi)} > N_s^{(k)}$, we can follow a similar approach and express the MAI from user k as the summation of $N_s^{(k)}$ terms, which form a 1-dependent sequence. Then, as $N_s^{(k)} \longrightarrow \infty$,

$$\frac{1}{\sqrt{N_s^{(k)}}} \sum_{l=0}^{N_s^{(k)}-1} \hat{M}_{k,l} \sim \mathcal{N}\left(0\,,\frac{1}{N_h^{(\xi)}}\right), \qquad (24)$$

where $\hat{M}_{k,l}$ is the interference related to the lth frame of user k.

Then, for large $N_s^{(k)}$, M_k is approximately distributed as $\mathcal{N}(0\,, E_{rp}^{(k)} \frac{N_s^{(k)}}{N_h^{(\xi)}})$. However, since the total gain $N_c = N_s^{(k)} N_h^{(k)}$ is constant for all users, the variance is the same as that of equation (14).

All in all, for large values of $\min\{N_s^{(k)}, N_s^{(\xi)}\}$, the distribution of the MAI from user k is approximately given by (14). □