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An Adaptive UWB Modulation Scheme for Optimization of Energy, BER, and Data Rate

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Abstract—**For many networks, different types of data require various QoS (quality of service) constraints such as bit error rate (BER), data rate, or energy dissipation. High data rate, low power dissipation, and simple RF circuitry make ultra wideband (UWB) an attractive technology to meet many QoS requirements. Typical UWB systems are built to meet QoS constraints even under the worst environmental conditions, although the worst environmental conditions occur infrequently. To prevent this waste of resources, we propose a UWB physical layer that adapts its modulation scheme to efficiently meet QoS requirements. The system employs *m*-ary PPM modulation and adapts its pulse repetition interval (PRI) and/or the number of bits per symbol ($\log_2 m$). Compared to a non-adaptive system, the adaptive system can improve BER up to 50%, energy by 60%, or data rate by 260%.**

Key Words – **UWB, modulation, PPM, adaptive systems, sensor networks, ad hoc networks**

I. INTRODUCTION

Since the FCC's historic allocation of spectrum for ultra wideband (UWB) in February of 2002, UWB systems have attracted an enormous interest from scientific, commercial, and military sectors. Compared to traditional narrowband communication systems, UWB has several advantages such as high data rate, low radiated power, and simple RF circuits. In addition, UWB has a radar capability with applications such as ranging and location awareness, which are important building blocks for many sensor applications and network protocols [1]-[2]. Due to these and many other desirable properties, UWB is an attractive technology for applications such as low-power sensor networks [3]. Adaptive systems benefit some major commercial standards [4], so we propose an adaptive UWB system to benefit sensor networks.

As sensing technologies advance, sensors become more accurate, sophisticated, and versatile [5]. As a result, large sensor networks tend to generate a considerable volume of aggregate data. Depending on the application and the specific type of data, the communications system must meet various quality of service (QoS) constraints – e.g., bit error rate (BER), data rate, or energy dissipation – at different times. Sensor networks require a low BER for control data [6] and high data rate for video or real time data [7]. Further, sensor networks always require energy efficiency since nodes have limited energy resources such as a battery or energy scavenging hardware [8]. Typical communications systems are built to meet these QoS constraints even under the worst environmental conditions. However, a communications system operates in the worst conditions in less than 5 % of its operating scenarios, so it wastes valuable resources as a result. Existing approaches to meet QoS requirements in sensor networks focus on the medium access control (MAC) layer and above, but these optimizations are often application dependant [9], [10]. Our adaptive UWB system meets such QoS requirements in the physical layer for any application.

The adaptive UWB system is motivated by the characteristics of *m*-ary pulse position modulation (PPM), which is a common modulation scheme for UWB [11]. With *m*-ary PPM modulation, a UWB system may easily adapt its pulse repetition interval (PRI) and/or the number of bits per symbol ($\log_2 m$). For this paper, we define a modulation scheme as the combination of PRI and *m*. Thus, the modulation scheme will affect the data rate and the required E_b/N_0 ratio – where E_b is the bit energy and N_0 is the noise level – to meet a BER target. Environmental conditions vary depending on the transmitter-receiver distance and the level of interference, and QoS constraints change depending on the type of data. We find that adapting the modulation scheme for various environmental conditions and QoS criteria improves overall BER, energy efficiency, and data rate.

The remainder of the paper is organized as follows. Section II explains our adaptive resource allocation strategy and our proposed UWB system. Section III discusses the method of finding suitable modulation schemes for given environmental conditions and QoS criteria. Section IV compares the performance of an adaptive system to a conventional, non-adaptive system. Section V concludes the paper.

II. BACKGROUND

A. Adaptive Resource Allocation

Under the conditions of dynamic traffic, unpredictable signal propagation, and frequent network topology changes, traditional communications systems with fixed resources are inadequate to efficiently meet variable QoS requirements. A non-adaptive system provides resources to meet the worst environmental conditions and most demanding QoS requirements at all times, so it wastes resources.

To efficiently meet QoS requirements, we propose to dynamically configure a UWB system with the resource allocation procedure in Figure 1.

In Figure 1, the first step in the resource allocation procedure examines the current QoS requirements, the resources of each node, and the current environmental conditions. The second step identifies a suitable system configuration to meet the current requirements, resources, and environmental conditions through a cost function. The third step allocates available resources to achieve the desired QoS. For the first step, we include the interfaces in Figure 2 for the physical layer, application layer, and MAC layer to communicate environmental conditions, QoS requirements, and resources to the *adaptive configuration block* (ACB). In this paper, the QoS requirements include data rate, BER, and energy dissipation. The environmental conditions include link distance and level of interference, and the resources are the possible values of PRI and *m*. This information is sent to the target node during the configuration period of a transaction. For carrier sense multiple access/collision avoidance (CSMA/CA), the information is included in a request to send (RTS) message. For time division multiple access (TDMA) protocols such as IEEE 802.15.3, the information is sent to the piconet coordinator (PNC) while requesting a time slot.

In the second step, a node selects the optimal modulation scheme, so the systems must have *a priori* knowledge of the characteristics of each possible configuration. This necessitates characterizing quantitative relationships among the modulation schemes, the data rate, the channel conditions, and the E_b/N_o required to meet a target BER. We develop a cost function to optimally allocate the appropriate resources. System characterization and resource allocation are the focus of this paper and are discussed in detail in Section III.

In the third step, systems must allocate resources for the appropriate modulation scheme. The target node configures its modulation scheme after notifying the initiating node of the chosen modulation scheme. The initiating node extracts the suggested modulation scheme from either a clear to send (CTS) packet for CSMA/CA or from the beacon of a PNC for IEEE 802.15.3. Note that nodes transmit control packets with a common modulation scheme. However, nodes transmit data with the most efficient modulation scheme that is supported. As environmental conditions change, a transmitter and a receiver must determine an appropriate method to reallocate their resources. Periodic updates result in no improvement if no data is sent between updates. Updates prior to every transaction can incur large overhead if the system topology and environmental conditions change slowly with respect to the transaction rate. Therefore, for simulation, we change a system configuration only if it results in an overall improvement in a parameter of interest. Each new allocation should exist long enough to offset any overhead from the reallocation algorithm. Network level simulations show significant overall benefit to the network with this strategy.

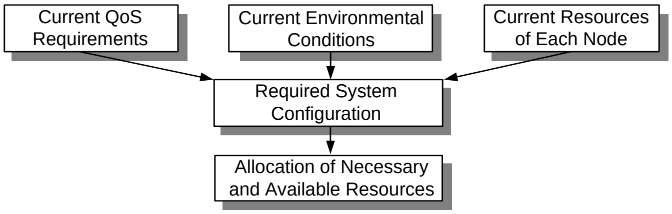

Figure 1: Proposed Approach for Resource Allocation

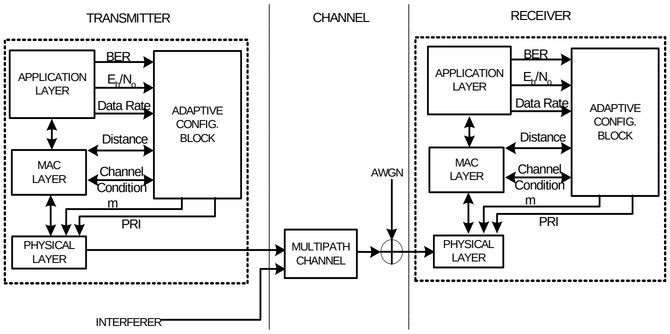

Figure 2: Block Diagram of Adaptive UWB System

B. UWB System

Each adaptive system consists of a transmitter, receiver, MAC layer, application layer, and ACB as shown in Figure 2. Other network layers that do not interact with the ACB are omitted from the figure. The simulations consider a transmission through a channel model that includes AWGN, multipath effects, and also a possible source of interference. Note that coding would achieve better performance in a practical system but it is omitted from the model to focus on the adaptive modulation scheme.

The transmitter modulates an input bit stream into a train of Gaussian monopulses with center frequency of 6.85 GHz and a bandwidth of 7.5 GHz. Energy outside the 3.1 GHz to 10.6 GHz range is attenuated with a bandpass filter to meet the FCC mask. The PPM pulse train is described in (1).

$$\mathrm{PPM}_{\mathrm{TX}}(\mathrm{t}) = \sum_{\mathrm{j}=0}^{\mathrm{N}-1} \mathrm{p}\left(\mathrm{t} - j \cdot \mathrm{PRI} - n\mathrm{T}_{\mathrm{P}}\right) \qquad (1)$$

The function p(t) is a Gaussian monocycle pulse, the parameter n specifies the modulation index, T_p is the duration of a pulse, and the PRI is the inverse of the symbol rate. The system uses m different non-overlapping pulse positions. The combination of m and PRI constitute a modulation scheme, which the ACB adjusts based on the environmental conditions and QoS requirements.

Using the energy efficient pulse generator of [12], PPM is particularly suited to an adaptive system. The various m-ary modulation schemes and PRI values are easily changed through a programmable delay unit. Thus, the generator can generate different m-ary modulation schemes and different PRI values with no architectural modifications.

The channel model is Cassioli et al.'s indoor UWB channel model [13], which considers large-scale and small-scale effects. Multipath effects may last up to 300 ns, although, on average, over 92% of energy is dissipated after 100 ns.

The performance of a basic correlation receiver is rather poor, since the total energy is spread over the multipaths, and the first multipath contains relatively little energy compared with the total energy. Therefore, we consider a frequency domain receiver that harvests the energy dispersed over the multipaths [14]. Compared to a conventional rake receiver, the proposed energy harvester reduces power dissipation, captures more energy, and requires simpler hardware. Since the receiver collects frequency domain samples, the circuit complexity is independent of the number of multipaths and modulation type. Further, the receiver demodulates PPM data based on the phase of the frequency components, so it will not incur greater implementation complexity for larger values of *m*. Finally, the sampling rate, which may be programmable, is based only on the PRI, so it is provides efficient implementation of a wide range of modulation schemes.

III. ADAPTIVE MODULATION SCHEME

The overall strategy for choosing a modulation scheme is motivated by the behavior of PPM in different environmental conditions. For a UWB system with PPM, several types of interference are possible. Co-channel interference occurs in a network when the target system captures the intended signal while one or more additional UWB systems transmit simultaneously. Inter-symbol interference (ISI) is such that a delayed multipath from the previous symbol interferes with the current symbol. In contrast, intra-symbol interference may cause a multipath from a current symbol to provide a higher correlation than the first multipath, which causes misinterpretation of the current symbol. ISI increases as PRI decreases, while the effects of intra-symbol interference and co-channel interference increase as *m* increases [11]. Thus, configurations with high *m* and a short PRI are more susceptible to interference, which eventually limits the performance regardless of the E_b/N_0. In contrast, configurations with low *m* and a long PRI are less susceptible to interference, and therefore the performance is more limited by the E_b/N_0 ratio. Therefore, for low E_b/N_0 ratios, modulation schemes with high *m* are preferable. However, for higher E_b/N_0 ratios, the interference dominates the noise, and modulation schemes with low values of *m* are preferable.

In this paper, the *local cost function*, β, of a transaction is

$$\beta = \frac{BER \cdot E_b/N_0}{Data\ Rate} \qquad (2)$$

The BER is a function of *m*, *PRI*, E_b/N_0, channel impulse response *h(x)*, and interference *i(x)*. The E_b/N_0 is a function of the transmitter-receiver distance and the maximum radiated energy allowed for a given data rate. The data rate depends only on the PRI and *m*.

$$BER = W\left(E_b/N_0\,, PRI, m, h(x), i(x)\right) \qquad (3)$$

$$E_b/N_0 = Y\left(dist, m, PRI\right) \qquad (4)$$

$$Data\,Rate = (\log_2 m)/PRI \qquad (5)$$

Thus, from (2)-(5), $\beta(z)$ defines the local cost function, where *z* is a set of environmental and QoS 6-tuples **[*E_b/N₀*, *m*, *PRI*, *h(x)*, *i(x)*, *dist*]** within *Z*, the set of all possible 6-tuples.

$$\beta(z) = \frac{PRI \cdot W\left(E_b/N_0\,, PRI, m, h(x), i(x)\right) \cdot Y\left(dist, m, PRI\right)}{\log_2 m} \qquad (6)$$

When environmental conditions vary, the local cost function is described in terms of a *local expected cost function* as in (7) for a given probability distribution *p(z)*.

$$\overline{\beta} = \sum_{\forall z \in Z} \beta(z) \cdot p(z) \qquad (7)$$

In this paper, the choice of modulation scheme is based on optimizing the local expected cost function (as opposed to a global cost, which is the sum of all local cost functions in a network). Therefore, a configuration is said to be optimal if it costs less than any other possible configuration for the given environmental and QoS parameters.

Numerical gradient-based optimization techniques can be used to minimize or maximize the cost function. However, gradient calculations can be costly for implementation, and hence, calculation may consume more resources than it saves. To reduce implementation complexity, the nodes use linear approximations to choose the optimal modulation scheme for the current operating conditions.

Next, we consider the cost function from the perspective of three likely scenarios that sensor nodes may encounter.

A. Minimum BER

Consider the update of the microcode of some nodes in a network. The microcode must be transmitted error free and may traverse several hops, thus increasing the probability of error. Therefore, the nodes involved in the transfer attempt to minimize the cost function by minimizing BER with an appropriate modulation scheme. FCC limitations constrain the radiated power level and the network fixes the data rate.

Figure 3 plots BER vs. E_b/N_0 for different m-ary PPM modulation schemes for a constant data rate of 25 Mbps. The modulation schemes operate at different PRIs to maintain the data rate. The 2-ary PPM operates at a PRI of 40 ns, 4-ary at 80 ns, 8-ary at 120 ns, 16-ary at 160 ns, and 32-ary at 200 ns.

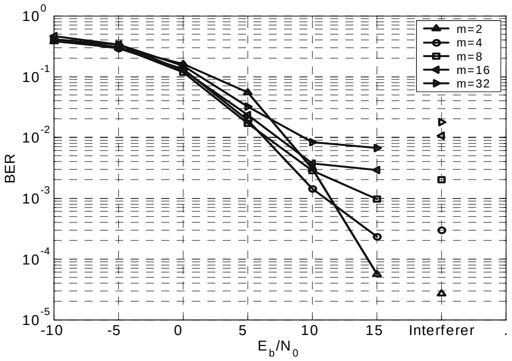

Figure 3: BER vs. E_b/N_0 at a Data Rate of 25 Mbps

As the hop distance changes, so too will the E_b/N_0. For all *m*-ary modulation schemes, the BER decreases as E_b/N_0 increases, but the rate at which it decreases depends on the modulation scheme. For the case marked “Interferer,” the source of errors is co-channel interference with an SINR of 0 dB. Each ACB pair chooses the modulation scheme that minimizes BER, which also minimizes the cost function for this type of data. From Figure 3, the ACB would choose 8-ary PPM for E_b/N_0 = 5 dB, 4-ary PPM for E_b/N_0 = 10 dB or 2-ary PPM for strong interference.

B. Maximum Data Rate

Next, we consider a network where throughput has priority over BER and energy. For example, a mobile video sensor network detects an intruder, so the attendant desires to view as much video data as possible. This type of application has some predefined minimum BER for acceptable video quality. Therefore, depending on the channel condition, the ACB chooses a system configuration to maximize data rate for a target BER and given E_b/N_0. For this type of application, maximizing data rate minimizes the cost function.

Figure 4 shows the maximum data rate possible at each E_b/N_0 compared to a non-adaptive system operating at a data rate of 25 Mbps. When E_b/N_0 = 5 dB, 8-ary PPM provides the highest data rate of 100 Mbps and meets the target BER. When conditions change to E_b/N_0 = 15 dB, the ACB chooses 4-ary PPM to provide the highest rate of 68 Mbps. A non-adaptive system is forced to maintain a 25 Mbps data rate to meet the minimum BER in all channel conditions.

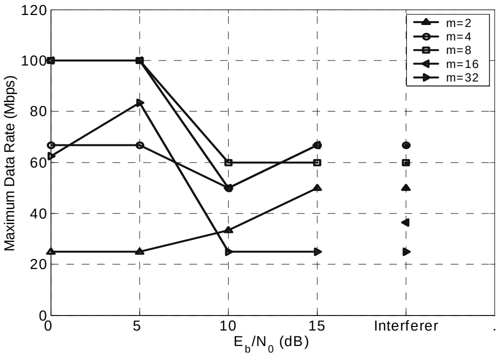

Figure 4: Maximum Data Rate vs. E_b/N_0

C. Minimum Energy

For energy-constrained sensor networks, minimizing the transmitted energy per bit is of significant interest. Such networks often adjust their output energy to meet only the minimum QoS requirements. The ACB further reduces energy consumption by choosing the modulation scheme that meets the QoS requirements with minimum E_b.

Figure 5 shows the energy required in each configuration for two different QoS scenarios. First, when the target BER is 5×10^{-3} and the data rate is 33 Mbps (QoS1), the 4-ary PPM scheme requires the minimum E_b to meet the QoS requirements. Likewise, if the QoS requirements change such that the target BER is 2×10^{-2} and the data rate is 80 Mbps (QoS2), then the ACB switches to 16-ary PPM. In general, for low BER and data rates, the ACB chooses lower order *m*-ary PPM schemes. For higher BER and data rates, the ACB chooses higher order *m*-ary PPM schemes.

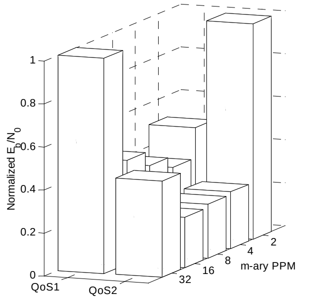

Figure 5: E_b for Various QoS Requirements

IV. SIMULATION RESULTS

The adaptive UWB system in Figure 2 was modeled in ADS (Advanced Design System) and compared to a non-adaptive UWB system for varying channel conditions and QoS goals. The simulations considered 5 different values of *m*, which were 2, 4, 8, 16, and 32 with a PRI that ranged from 10 to 210 ns.

The first case is a microcode transaction that requires the minimum BER, has a fixed data rate, and radiates the maximum allowed E_b. The distances of each transaction determine the E_b/N_0 such that it varies from 0 dB to 15 dB in integer steps, and the distribution is shown in (8).

$$p_{Eb/No|m,PRI,dist} = \begin{cases} 0.0625, & 0dB \le E_b/N_0 \le 15dB \\ 0, & else \end{cases} \tag{8}$$

Also, an interferer causes the SINR to be 0 dB 10% of the time. The channel impulse response is a random instance of the Cassioli model for each transaction, and the ACB considers *m* and *PRI* values that result in a constant data rate.

Table I compares the costs of five non-adaptive systems to the costs of an adaptive system. The costs are given in (7), and the non-adaptive systems cannot change *m* or *PRI* to reduce the cost. The last column shows the ratio of the BER of the adaptive system to that of the worst performing non-adaptive system. The adaptive system always performs better than the best performing non-adaptive system at a given data rate, and it can approximately halve BER (or cost) as compared to 2-ary PPM. The adaptive system performs even better if the data rate changes dynamically. This is because the adaptive system chooses the configuration with minimum BER, whereas the non-adaptive system always meets the BER for the worst case.

TABLE I: BER OF NON-ADAPTIVE VS. ADAPTIVE SYSTEM

Data Rate	*m=2*	*m=4*	*m=8*	*m=16*	*m=32*	*Adaptive*	*Min. Ratio*
50 Mbps	0.0474	0.0310	0.0303	0.0289	0.0355	0.0263	55.3%
25 Mbps	0.0418	0.0239	0.0233	0.0252	0.0322	0.0212	50.7%

Next, we consider an adaptive system that maximizes the data rate for a target BER in various channel conditions. The environmental and QoS parameters are the same as above, but now the adaptive system increases the data rate by choosing an appropriate system configuration. Any non-adaptive system must operate at the fixed data rate of 25 Mbps to meet the target BER even in the best channel conditions. Table II compares simulation results of the adaptive UWB system and the non-adaptive UWB system. In every case, the adaptive system provides a faster data rate than a non-adaptive scheme. The data rate (or cost) can be improved by up to 260 % for the data rate of 25 Mbps. Generally, the improvement in data rate is larger at lower data rates because the ACB can choose from a larger range of PRI values for the system configuration to meet the QoS parameters whereas at higher data rates, the ACB chooses from a much smaller range of PRI values resulting in a more limited improvement.

TABLE II: SPEED OF NON-ADAPTIVE VS. ADAPTIVE SYSTEM

Non-Adaptive	*Adaptive*	*Increase*
50 Mbps	84.1 Mbps	68.2%
25 Mbps	90.4 Mbps	261%

Finally, we consider an adaptive system that minimizes the transmitter output energy over various QoS constraints. The first QoS constraint requires a BER of 5×10^{-3} and a data rate of 33 Mbps, and this represents the case of distributing microcode over several hops. The second case requires a BER of 2×10^{-2} and a data rate of 80 Mbps, and this represents the case of video data. Table III shows the normalized E_b values obtained from simulation for the two QoS goals. Again, the adaptive scheme performs best, reducing energy (or cost) by up to 61% over a non-adaptive system with m=2.

TABLE III: ENERGY OF NON-ADAPTIVE VS. ADAPTIVE SYSTEM

M=2	*m=4*	*m=8*	*m=16*	*m=32*	*Adaptive*	*Min. Ratio*
1.00	0.415	0.443	0.477	0.964	0.395	39.5%

V. CONCLUSION

We have proposed a UWB system that adapts its resources to efficiently meet QoS requirements in dynamic environmental conditions. The system is particularly suitable for applications such as sensor networks, which have demanding QoS requirements that change for various types of data. The configuration block is independent of the application and network layers, and it configures the UWB radio based on the current environmental conditions, resources, and QoS requirements. Since the worst environmental conditions occur infrequently, the adaptive system conserves resources that are typically wasted in a non-adaptive system.

An adaptive UWB system is motivated by the characteristics of m-ary PPM in various environmental conditions. In general, for low values of E_b/N_0, the noise dominates the interference, and therefore, efficient modulation schemes with high m are preferable. However, for larger values of E_b/N_0, the interference dominates the noise and modulation schemes with low values of m are preferable. The choice of the modulation scheme is based on optimizing a cost function that is defined in terms of E_b/N_0, BER, and data rate. An optimal solution to the cost function is prohibitively costly, so it is necessary to use linear approximations to efficiently configure the system.

Simulations of the adaptive system show that it improves performance significantly as compared to a conventional non-adaptive system under variable environmental and QoS requirements. The adaptive system improves BER by 50%, data rate by 260%, or energy by 60% without sacrificing performance of any other parameter.

REFERENCES

[1] S. Basagni, I. Chlamatac, V. R. Syrotiuk, & B. A. Woodward, "A distance routing effect algorithm for mobility (DREAM)", *Proc. Mobicom '98*, Dallas, TX, pp. 76-84, Oct. 1998.

[2] J. Liu, P. Cheung, L. Guibas, and F. Zhao, “A dual-space approach to tracking and sensor management in wireless sensor networks,” *Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications* (WSNA 2002), pp 131-139, Sep. 2002.

[3] I.F. Akyildiz, S. Weilian, Y. Sankarasubramaniam, and E. Cayirci, “A survey on sensor networks” *IEEE Communications Magazine*, vol.40, iss. 8, pp. 102-114, Aug. 2002.

[4] S. Nanda, K. Balachandran, and S. Kumar, “Adaptation techniques in wireless packet data services,” *IEEE Communications Magazine*, Jan. 2000.

[5] M. Perkins, N. Correal, and B. O'Dea, “Emergent wireless sensor network limitations: a plea for advancement in core technologies,” *Proceedings of IEEE International Conference on Sensors*, Vol.2, pp.1505-1509, 2002.

[6] C.-Y. Wan, A. T. Campbell, and L. Krishnamurthy, “PSFQ: a reliable transport protocol for wireless sensor networks,” *Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications* (WSNA 2002), pp. 1-11, Sep. 2002.

[7] Chenyang Lu, B.M. Blum, T.F. Abdelzaher, J.A. Stankovic, Tian He, “RAP: a real-time communication architecture for large-scale wireless sensor networks”, Real-Time and Embedded Technology and Applications Symposium Proceedings, pp. 55 – 66, Sept 2002

[8] R. Min, et. al, ”Energy-centric enabling technologies for wireless sensor networks,” *IEEE Wireless Communications*, vol. 9, no. 4, pp. 28-39, Aug. 2002.

[9] S. Singh and C.S. Raghavendra, “PAMAS – Power aware multi-access protocol with signaling for ad hoc networks,” *ACM Sigcomm Computer Communication Review*, Vol. 28, No. 3, pp.5-26, July 1998.

[10] C. K. Toh, “Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks,” *IEEE Communications Magazine*, Vol. 39, No. 6, pp. 138-147, June 2001.

[11] N.J. August, W.C. Chung, and D.S. Ha, “Energy efficient methods of increasing data rate for ultra wideband (UWB) communications systems,” *IEEE Conference on Ultra Wideband Systems and Technologies (UWBST 2003)*, pp. 280-284, Nov. 2003.

[12] K. Marsden, H.-J. Lee, D.S. Ha, and H.-S. Lee, “Low power CMOS re-programmable pulse generator for UWB systems,” *IEEE Conference on Ultra Wideband Systems and Technologies (UWBST 2003)*, pp. 443-337, Nov. 2003.

[13] D.Cassioli, M.Z. Win, and A.F. Molisch, “The ultra-wide bandwidth indoor channel: from statistical model to simulations,” *IEEE Journal on Selected Areas in Communications*, Vol. 20, No. 6, pp. 1247-1257, Aug. 2002.

[14] H.-J. Lee, D.S. Ha, and H.-S. Lee, “A frequency-domain approach for all-digital CMOS ultra wideband receivers,” *IEEE Conference on Ultra Wideband Systems and Technologies (UWBST 2003)*, pp. 86-90, Nov. 2003.