Impact Of Ultra Wideband (Uwb) Radio Range On Wireless Sensor Networks

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Abstract - An important application of wireless sensor networks is monitoring factory systems and devices. Typical narrowband radios may be forced to increase their radiated power to maintain network connectivity in the harsh radio environment of a factory. I-UWB radios have many advantages over narrowband radios in a sensor network. However, the radiated power of I-UWB radios is severely limited by regulations, so they must extend radio range through other means. We derive the limits of I-UWB radio range through link budget calculations based on the Friis equation in free space for a realistic I-UWB system that includes the effects of data rate, signal-to-noise ratio, antenna gains at the transmitter and the receiver, and the path loss exponent. From the calculations, we obtain some practical relationships between I-UWB system parameters and network connectivity.

I. Introduction

Wireless sensor networks have garnered a great deal of recent interest from industry and academia [1],[2]. An important application is monitoring factory systems and devices. To maintain network connectivity in the harsh radio environment of a factory, a radio may be forced to dynamically adjust its range. Typical narrowband radios modify their range by adjusting the radiated power. The radiated power directly affects the link distance and inversely affects the amount of co-channel interference.

There has been a great deal of interest in ultra wideband (UWB) radio for wireless sensor networks. Impulse based UWB (I-UWB) is particularly attractive for sensor networks in factories due to its resilience to multipath interference, simple transceiver circuitry, accurate ranging ability, and low transmission power [1]-[4].

To operate in the harsh radio environment of a factory, an I-UWB radio should be able to dynamically adjust its range. The FCC limits the average radiated power of I-UWB to levels that are orders of magnitude less than typical narrowband radios. Although the low radiated power is advantageous in conserving energy, it prevents I-UWB radios from extending their range by simply increasing the radiated power like a traditional narrowband radio [3]. In this paper, we show that an I-UWB radio can extend its range without increasing average radiated power or significantly increasing hardware complexity.

The paper is organized as follows. Section II briefly presents the advantages of I-UWB for factory system monitoring. Section III investigates the range of I-UWB radios, and Section IV presents simulation results on network connectivity. Section V concludes the paper.

II. Advantages of UWB

FCC regulations define any UWB system as one with a fractional bandwidth greater than 0.20 or an absolute bandwidth greater than 500 MHz. FCC regulations also require an UWB system to emit very low average power, -41.3 dBm/MHz, over the bandwidth from 3.1 GHz to 10.6 GHz. Thus, the average radiated power for the entire bandwidth of 7.5 GHz is less than 560 μW.

I-UWB systems communicate by modulating a train of pulses instead of a carrier. The carrierless nature of I-UWB results in simple, low-power transceiver circuitry, which does not require intermediate mixers and oscillators. As the pulse duration decreases, the increased bandwidth results in many advantages for factory sensor networks:

- Ranging accuracy is determined by the bandwidth, so accurate (under a centimeter) ranging and position location are now built into the radio interface.

- Channel capacity increases linearly with bandwidth, whereas it only increases logarithmically with power. For a given offered load, a higher data rate increases throughput, decreases delay, and decreases collisions.
- The wide bandwidth leads to precise multipath resolution. Further, the pulse repetition interval may be adjusted to avoid inter-symbol interference. Resilience to harmful multipath effects enables sensors to be placed in areas inhospitable to narrowband systems, such as inside a factory packed with metallic objects.
- The 7.5 GHz of bandwidth allows many opportunities for multiple access.
- The wide bandwidth results in a low power spectral density, which in turn results in low probability of intercept and detection.
- The low frequency components have excellent material penetration capabilities.

III. Estimation of UWB Radio Range

The range of a radio system is usually limited by 1) noise and interference, 2) regulations on radiated power, 3) available bandwidth, and 4) implementation efficiency. I-UWB is constrained mostly by strict FCC emission limits. From the Friis equation, the following determine the path loss and range for I-UWB in free space [6],[7].

$$PL_d=FL-10*log(DR)-SNR-NF+10*log(BW/7.5)+G_{ant}-PL_{ref} \quad (1)$$

$$d \;\; = 10.\hat{\ }(PL_d./(10*n)) \quad (2)$$

PL_d is the path loss at range of d meters; FL is the system gain at the fundamental limits; DR is the data rate in bps; SNR is the E_b/N_0 in dB; NF is the noise figure in dB representing implementation loss; BW is the bandwidth in GHz; G_{ant} is the antenna gain in dBi; and PL_{ref} is the path loss at the close-in reference distance in dB. The system gain FL is defined as the required power for obtaining a data rate of 1 bps. For I-UWB, the system gain of 173 dBm/bps is derived from three fundamental limits: the maximum radiated power (=-41.3 dBm/MHz) of the I-UWB signal over its maximum bandwidth (BW_{max}=7.5 GHz), the minimum SNR from Shannon's channel capacity theorem ($E_b/N_{0\ min}$ = -1.59 dB), and the thermal noise at room temperature (=-174 dBm/Hz). The parameter n in (2) is the path loss exponent. The path loss exponent is 2 for free space and varies depending on channel conditions such whether the path is line-of-sight and whether the environment is indoor or outdoor.

We consider the following default parameter values in our range calculations.

- Data rate (*DR*): 10 Mbps
- Bandwidth (*BW*): 1 GHz
- Required SNR (*R-SNR*): 8.4 dB
- Noise figure (*NF*): 3 dB
- Antenna gain (G_{ant}): 0 dBi
- Path loss at the reference distance (PL_{ref}): 44 dB
- Path loss exponent (n): 2

Holding all other parameters at the default value, we vary one parameter of interest at a time to investigate its impact on I-UWB radio range. Figure 1 shows the calculated I-UWB ranges as a parameter of interest is swept. Six points x1 through x6 on the *x*-axis denote the six values of a parameter of interest, and their values are listed in Table 1. For example, consider *DR* as the parameter of interest. The x1 value of *DR* is 30 Mbps and the x2 value is 25 Mbps and so on, while the other paramters maintain their default values of *BW* = 1 GHz, *R-SNR* = 8.4 dB, *NF* = 3 dB, and G_{ant} = 0 dB. Note that the ranges shown in Figure 1 are optimistic as the path loss exponent n is set to 2 (which is for free space). Realisitically achievable ranges will be shorter, because I-UWB channel conditions will likely result in $n > 2$.

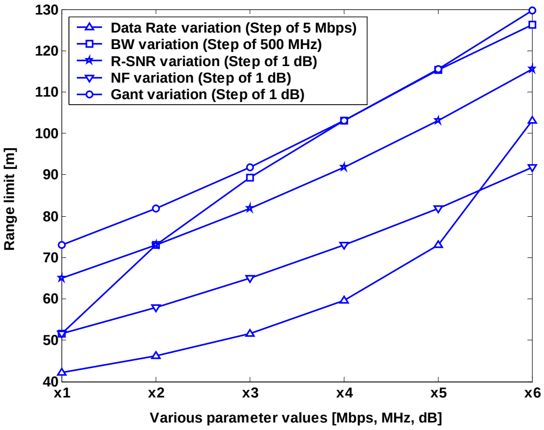

Figure 1: Range versus various parameter values.

Table 1: Parameter values for the x-axis in Figure 1.

Parameter	*x1*	*X2*	*x3*	*X4*	*X5*	*x6*
Data Rate (Mbps)	30	25	20	15	**10**	5
BW (GHz)	0.5	**1**	1.5	2	2.5	3
R-SNR (dB)	9.4	**8.4**	7.4	6.4	5.4	4.4
NF (dB)	6	5	4	**3**	2	1
G_{ant} (dB)	**0**	1	2	3	4	5

(*Note: Default values are in* **bold**.)

As shown in Figure 1, the range is more sensitive to the data rate and the bandwidth than to the other three parameters. The range varies from 42 meters to 103 meters as the data rate changes from 30 Mbps to 5 Mbps and from 51 meters to 127 meters as the bandwidth varies from 0.5 GHz to 3 GHz. Fortunately, the two parameters can readily be changed dynamically during operation with small additional hardware cost. Data rate can be changed by varying modulation or pulse rate, and bandwidth can be changed by varying pulse shape or via pass-band filtering. Thus, both data rate and bandwidth are good candidates to dynamically modify the radio range in an I-UWB system.

Finally, note that we set BW_{max} to 7.5 GHz in computing the fundamental system gain of 173 dBM/bps. Varying the *BW* in our calculations does not affect this fundamental limit, because the effects of *BW* are determined separately in the term *10*log(BW/7.5)* in (1).

IV. Network Connectivity Simulation

In a harsh radio environment, it may be necessary to adjust the radio range dynamically to ensure network connectivity and also to minimize co-channel interference from short hops [8]. As shown above, the range of an I-UWB radio link may be adjusted without varying the average radiated power. Therefore, in this section, we perform network simulations that show the effects of I-UWB system parameters on network connectivity.

A. Simulation Setup

In the simulations, we consider a network topology with 225 nodes placed randomly in a 50 meter × 50 meter two-dimensional square. A network is considered to be connected if each node can reach every other node either through some multi-hop route or through direct radio contact. We simulate the effects of each I-UWB system parameter on the connectivity of 20 random topologies to show the average trend for each I-UWB system parameter.

The simulations adjust three I-UWB system parameters, one at a time, to gradually increase the range of each unconnected node until the network becomes connected. The three I-UWB simulation parameters are bandwidth (*BW*), required SNR (*R-SNR*), and pulse repetition interval (PRI). The PRI is the inverse of the pulse rate, which is directly related to the data rate scaled by the coding rate and spreading rate. The default value of the PRI is set to 90 ns (which corresponds to a data rate of about 11.1 Mbps without coding or spreading).

B. Simulation Results

First, we consider the simplest method of extending range, which is unique to I-UWB. We increase the PRI until the network is connected. As the PRI increases, the energy per pulse can also be increased while maintaining the same average power. Therefore, the E_b/N_0 is higher and the range also increases.

Assuming a constant radiated power, Figure 2 shows the effect of PRI on the connectivity of the network. The *y*-axis denotes the probability that all nodes are connected. As the PRI increases from 70 ns to 80 ns, the network abruptly becomes connected. Therefore, to conserve power for this example, it is best to have a PRI of around 90 ns. Because the radiated power *P* is constant, the overall energy *E* required to transmit a packet of length *L* bits will be less for a shorter PRI (or equivalently a faster data rate) than a longer PRI as follows.

$$E = L * P * PRI \tag{3}$$

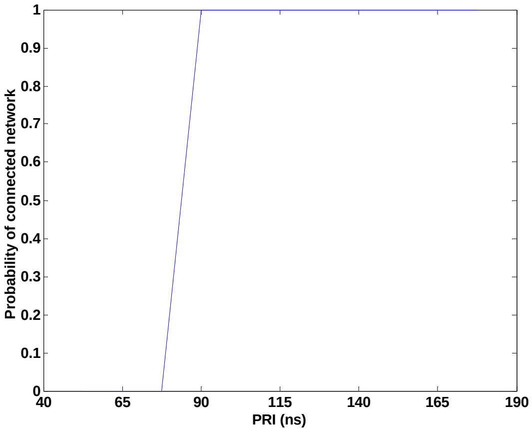

Figure 2: Probability(connected) vs. PRI

Secondly, we vary the signal bandwidth as shown in Figure 3. For a bandwidth above 1.5 GHz with the remaining default parameter values, the network is completely connected.

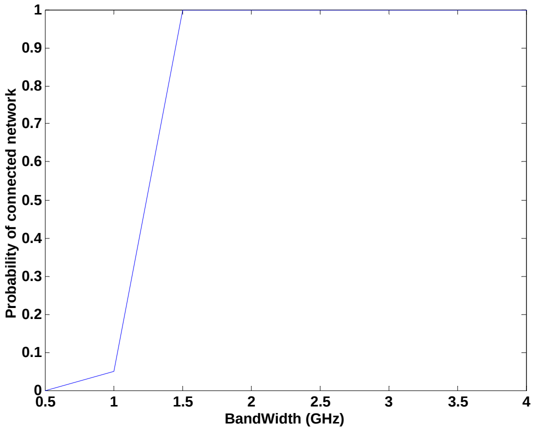

Figure 3: Probability(connected) vs. BW.

However, as the bandwidth increases in Figure 3, the radiated power also increases and so does the energy per bit for a constant data rate. Note that increasing the bandwidth may be accomplished dynamically through a programmable pulse generator such as [9] or through an adaptive filter.

Thirdly, we consider the effects of the required SNR (*R-SNR*) on the probability of the connectivity of the network. As the *R-SNR* decreases, the probability of connection will increase as shown in Figure 4. To change the *R-SNR*, we change the forward error correction coding with a convolutional code. Increasing the coding rate decreases the necessary E_b/N_0 at the receiver and also decreases the data rate due to the incurred redundancy of the code.

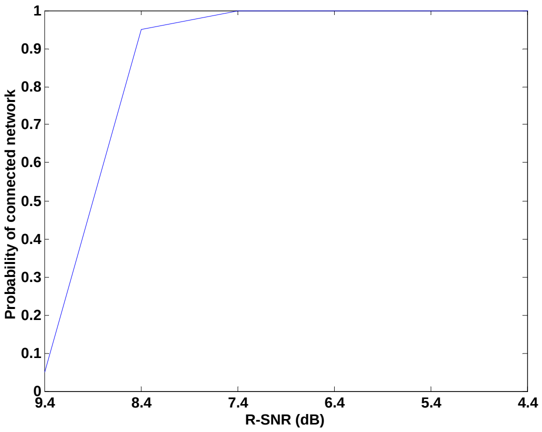

Figure 4: Probability(connected) vs. R-SNR.

V. Conclusion

In this paper, we investigated the impact of some I-UWB system parameters on radio range. The parameters are pulse repetition interval, bandwidth, required signal-to-noise ratio, noise figure (or implementation loss), and antenna gain. For a sensor network operating in a harsh radio environment such as a factory, it is critical to be able to adjust the radio range to ensure connectivity and to limit interference. For some random network topologies, we swept three parameters – the pulse repetition interval, the bandwidth, and the required SNR – to determine their effect on network connectivity.

To increase the probability of the network connectivity, an I-UWB radio may increase the pulse repetition interval, increase the bandwidth, or decrease the required signal-to-noise ratio. The general tendency of network connectivity versus I-UWB system parameters is an abrupt change to a connected network at some threshold value. Therefore, it is important to operate close to this threshold to conserve energy while maintaining connectivity. For our example system, the threshold points for network connectivity are 80 ns for the PRI and 1 GHz for the BW. In a practical sensor network, the easiest method of modifying range is through the PRI (data rate), which can readily be achieved with moderate additional control hardware.

References

[1] I.F. Akyildiz et al., “A Survey on Sensor Networks,” *IEEE Communications Magazine*, pp.102-114, August 2002.

[2] A.J. Goldsmith and S. B. Wicker, “Design Challenges for Energy-Constrained Ad Hoc Wireless Networks,” *IEEE Wireless Communications Magazine*, pp. 8-27, August 2002.J.H. Reed (Editor), *An Introduction to Ultra Wideband Communication Systems*, Prentice Hall, 2005.

[3] W.C. Chung, N.J. August, and D.S. Ha, “Signaling and Multiple Access Techniques for Ultra Wideband 4G Wireless Communication Systems,” *IEEE Wireless Communications*, Vol. 12, No. 2, pp. 46-55, April 2005.

[4] N.J. August, *Medium Access Control in Impulse-Based Ultra Wideband Ad Hoc and Sensor Networks*, Ph.D. Thesis, Dept. of Electrical and Computer Engineering, Virginia Tech, May 2005.

[5] 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*, pp. 280-284, November 2003.

[6] T.S. Rappaport, *Wireless Communications – Principles and Practice*, pp. 70-74, Prentice Hall, 1996.

[7] R. Aiello, J. Ellis, U. Kareev, K. Siwiak, and L. Taylor, *Understanding UWB – Principles & Implications for Low Power Communications*, Available at http://www.ieee802.org/15/pub/2003/Mar03/03157r1p802-15_wg-understanding_uwb_for_low-power_communications-a_tutorial.pdf, Mrach 2003.

[8] M.X. Gong, S.F. Midkiff, and R.M. Buehrer, “A Now Piconet Formation Algorithm for UWB Ad Hoc Networks,” *IEEE Conference on Ultra Wideband Systems and Technologies*, pp. 180-184, November 2003.

[9] 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*, pp. 443-337, November 2003.