Performance evaluation of the IEEE 802.15.4A UWB physical layer for Body Area Networks

Jérôme Rousselot, Amre El-Hoiydi, Jean-Dominique Decotignie
CSEM, Jaquet-Droz 1
2002 Neuchâtel
Switzerland
E-mail: jerome.rousselot@csem.ch

Abstract

The IEEE 802.15.4 standard is gaining momentum in the field of wireless sensor networks. The IEEE 802.15.4A draft specification proposes an impulse radio Ultra Wide Band physical layer. This technology aims at being robust against multipath propagation and multi user interference. In the context of body area networks, the impact of multi user interference must be evaluated precisely. It is modeled here with the Pulse Collision Model adapted to the draft standard. Numerical simulations show remarkable performance for communications between two distant groups of devices. While still acceptable, results were less encouraging when considering a large grid of devices. This suggests a sensitivity to near-far interference.

1. Introduction

Impulse Radio Ultra Wide Band (IR-UWB) [5] is a technology especially well suited for short and medium range communications. This technology is currently being investigated for use in Body Area Networks (BAN) [6, 3, 2], a technology enabling distributed wireless communications between miniaturized sensors and actuators carried by a person. Numerous applications have been identified in healthcare, sports and entertainment.

The IEEE 802.15.4A task group [1] is preparing a standard for an alternative IR-UWB physical layer. This draft standard defines a Time Hopping Burst Position Modulation (TH-BPM) scheme, in which it is proposed to transmit pulses in bursts.

This paper is organised as follows. Section 2 defines the System Model, Section 3 describes two BANs application scenarios and evaluate the adequateness of IEEE 802.15.4A by means of numerical simulations. Section 4 concludes the paper.

2. System Model

2.1. IEEE 802.15.4A Draft UWB Specification

The UWB specification proposes the use of 500 MHz channels. The combination of a channel and a preamble code (two are possible) defines a complex channel. This means that up to two independent networks can operate on the same channel. In this work, all considered devices share the same preamble code and are part of the same network. The simulations used the mandatory channel for the so called uwb low band (channel 3, center frequency: 4492 MHz). The complete list of parameters which were used can be found in Table 1.

The pulse shape must fit in a 2 ns chip time. Each bit is represented by a burst of a number of pulses. The bit value codes the position in time of
the burst. This is illustrated in Figure 1. Long guard
times are imposed to protect the signal from inter-
ference caused by its own multipath components.

In addition to the BPM scheme, a time hopping
sequence \( \theta_j \) is used to smooth the spectrum. The
symbol duration is noted \( T_s \), the xth bit \( b_x \), the burst
energy \( E_{T_x} \), the energy-normalized waveform of
the burst \( B_0(t) \) and the PPM shift is set to \( \frac{T_B}{2} \). The
transmitted signal can be expressed by

\[
s_{T_x}(t) = \sqrt{E_{T_x}} \sum_j B_0 \left( t - jT_s - \theta_jT_B - \frac{T_j}{2}b_j \right)
\]  

(1)

The value used for the burst energy \( E_{T_x} \) is
the maximum peak e.i.r.p. density allowed at this
frequency band by the US Federal Communication
Commission (FCC) and by the European Union: 0
dBM/50 MHz.

2.2. Channel Model

Simulations involving classical narrow-band
radios can generally consider the frequency con-
tant over the signal bandwidth when using the
Friis Transmission Formula:

\[
P_r(d) = EIRP \ast G_r \left( \frac{\lambda}{4\pi d} \right)^2
\]  

(2)

where \( EIRP \) is the Effective Isotropic Radiated
Power, \( G_r \) is the antenna gain at the receiver side, \( \lambda \) is the signal wavelength and \( d \) is
the distance between the transmitter and the receiver. This formula remains valid for UWB sys-
tems with the hypothesis that the receiver antenna
has a constant gain \( (G_r) \) over the signal bandwidth.
With the same assumption on the transmitter side: \( EIRP = P_t G_t \). When considering unit gain an-
tennas, the received power can be expressed as fol-
lows:

\[
P_r(d) = P_t \left( \frac{\lambda}{4\pi d} \right)^2
\]  

(3)

By evaluating this expression at a reference
distance \( d_0 \), it can be introduced in a frequency in-
dependent relation that takes into account non-line-
of-sight situations:

\[
P_r(d) = P_r(d_0) \left( \frac{d_0}{d} \right)^n
\]  

(4)

where \( n \) is a frequency independent path loss
exponent. Since no results on UWB propagation
in crowded environments could be found, the liter-
ature on UWB propagation inside and around the
human body was studied. [2] shows that the path
loss exponent value varies between 3.1 and 7.2 for
the body area propagation channel. Unsurprisingly,
the worst case happens when one of the devices is
placed on the front of the body and the other on the
back. Another interesting result from their work is
the importance of the distance between the antenna
and the body: a minimum of 5 mm greatly im-
proves signal propagation. A path loss exponent of
5.2, arbitrarily chosen between the extreme values,
was used in the numerical simulations presented.
below. Others [6, 3] have found slightly lower values: 4.1 and 4.4.

2.3. Pulse Collision Model

Multi User Interference is often an important source of performance degradation in wireless communications. An accurate statistical model is thus necessary in order to obtain valid results.[4] considers the physical process that leads to the occurrence of an error in the case of UWB correlation receivers followed by a ML detector.

A probabilistic approach of the problem leads to the following upper bound on the bit error rate, where the first term depends only on the signal to thermal noise ratio, and the second term evaluates all possible cases of multi user interference, pondered by their occurrence probability:

\[ BER \leq \frac{1}{2}erfc\left(\sqrt{\frac{E_u}{2N_0}}\gamma\left(\frac{T_s}{2}\right)\right) \]

\[ + \sum_{N_c=0}^{N_i} \frac{P_{CP}(N_c)^2}{2} \]

\[ \times \Omega\left(\frac{E_u}{N_0}\gamma\left(\frac{T_s}{2}\right), \frac{Z_{max}(N_c)^2}{2N_0\gamma\left(\frac{T_s}{2}\right)}\right) \]

This upper bound on the bit error rate is referred to as \( \widetilde{BER} \) in the remaining of this paper. This expression is the same one that can be found in [4], with the following modifications:

- the results are expressed in terms of the complementary error function \( erfc(x) \);
- the pulse waveform function is replaced by the burst waveform function;
- the repetition factor \( N_S \) is set to one.

2.4. Packet Error Rate

The packet error rate can be inferred from the BER upper bound by considering that the probability that each of the \( n \) transmitted bits has been decoded correctly:

\[ PER = 1 - (1 - \widetilde{BER})^n \]

The IEEE 802.15.4A draft specifies the use of a Reed-Solomon error correction code (\( RS_6(63, 55) \)). This code can detect and correct up to 8 erroneous 6-bits symbols. An upper bound on the probability of decoding \( i \) erroneous symbols in a packet of \( n \) data bits protected by \( c_{err} \) bits RS parity bits is given by:

\[ P(i\text{ err. symbols}) = \left[ \begin{array}{c} \frac{n+c_{err} \text{ bits}}{i} \\ i \end{array} \right] \]

\[ \times \left[ 1 - (1 - \widetilde{BER})^{6i} \right]^i \]

\[ \times \left( 1 - \widetilde{BER} \right)^{6i\left( \left[ \frac{n}{6} \right] - i \right)} \]

The first factor accounts for all possible positions of the \( i \) erroneous symbols. The product of the second and third factors give together the realization probability of 6 erroneous symbols.

And the packet error rate formula becomes:

\[ PER = 1 - \sum_{i=0}^{8} P(i\text{ erroneous symbols}) \]

3. Performance Evaluation

3.1. Body Area Networks

Body Area Networks (BAN) are a promising application field for wireless sensor networks. In healthcare, they will allow more accurate monitoring of life-critical parameters, and give more freedom of movements to the patients.

The first scenario studied below considers two groups of transceivers separated by a great distance. The sensors forming the first group asynchronously transmit data to receivers in the second group. It models a group of persons being monitored, their sensors transmitting the data back to several base stations located in a same region. In
the second scenario, the impact of an increasing number of transceivers in the vicinity of a node is studied. This models a uniform crowd in which each person is equipped with its own personal body area network.

Both scenarios share the same application requirements: each sensor makes 1024 measurements per second and each measurement is 12 bits long (a typical analog-to-digital converter bandwidth). A packet containing a 240 bits payload is sent every 19.6 ms. With a 2 bytes address field and 48 parity bits, the raw packet size is 304 bits. Radio bit rate is set to 0.85 Mbps (IEEE 802.15.4A Mandatory speed).

3.2. Aggregate Throughput

A group of nodes close to each other (average distance of two meters) transmit their data to another group 50 meters away. The packet error rate is evaluated with increasing numbers of nodes. The mean number of jammers is given by:

\[
Nb\text{ConcurrentUsers} = \frac{\text{throughput}}{\text{bitRate}}(nbTx - 1)
\]  

(9)

where \(\text{throughput}\) is the sensor throughput from the considered node, \(\text{bitRate}\) is the speed at which data is sent, and \(nbTx\) is the number of transmitters. Since \(Nb\text{ConcurrentUsers}\) is a real number, a linear interpolation of the BER is performed by considering \(\lfloor Nb\text{ConcurrentUsers} \rfloor\) and \(\lceil Nb\text{ConcurrentUsers} \rceil\) jammers. This interpolated value is then used to calculate the value of (8) in the expression of the aggregate throughput:

\[
AT = activeTx \times \text{throughput}(1 - \text{PER})
\]  

(10)

where \(\text{throughput}\) is the application data rate (12 kbps) and \(activeTx\) the number of simultaneously active transmitters.

The effect of packet size can be seen on Figure 2. It is significant: the aggregate throughput obtained with the smallest packet size is twice the one associated to the biggest one. This is due to the dependency on packet length \(n\) in (7). With the smaller packet size, a network of more than one thousand nodes can be successfully operated. This surprising result has two causes: duty-cycling and robustness to multi user interference. The duty cycling means that only a tiny fraction of the nodes are concurrently in activity. This is possible thanks to the high radio bit rate (almost one megabit per
The robustness to multi user interference is delivered by the burst position modulation of IEEE 802.15.4A standard, which exploits the temporal characteristics of impulse ultra wide band radios. From a qualitative point of view, the performance degrades smoothly when the maximal number of users is reached. This is a welcome additional result.

The effect of the error correction code has also been evaluated (See Figure 3). If error correction is not performed at the receiver, the performance drops sharply. In addition, the standard also proposes a second forward error correction code transmitted through binary phase shift keying (BPSK). As its decoding is optional, it has not been modeled here. Its use should deliver a further significant increase in transmission success.

Finally, in Figure 4, the system performance is evaluated when the application throughput is maximal. Again, the packet size varies, and the smallest one is associated with the best performance. As there is a constant number of error correction bits per packet, with a reduced packet size the ratio of redundancy bits to total packet size increases and so does the performance. The maximum number of users that the system can satisfy, between ten and fifteen, is much lower but still relevant for many applications.

3.3. Network Density

In the second scenario, the same application low data rate throughput (12 kbps per sensor) is considered. This time, the focus is on network density. Each node communicates with another node located 10 meters away. The nodes are uniformly distributed on a 100x100 square meters grid, approximating an infinite one. As can be seen in Figure 5, the network performs well with up to 1000 nodes on the grid (a density of 0.1). Around 1500 nodes, the performance starts degrading linearly with the biggest packet size (338 bits), while the two other packet sizes (548 and 1058 bits) allow to increase the network density up to around 0.2 nodes per square meters. After which their associated performances degrade as well, more abruptly for the second biggest packet size than for the smallest one. These results are not as good as in the first scenario. Indeed, this establishes a limit value of one node per five square meters, which is clearly not enough for body area networks appli-
cations. Since the results in the first scenario established that a high density could be reached, this could indicate a sensitivity to near-far effects.

As in the previous section, the simulations were also run with continuously transmitting nodes (Figure 6). The total acceptable number of nodes in the network decreases to 50 for the largest packet size and to 70 for the two other packet sizes, corresponding respectively to 1 node per 200 square meters and 1 node per 143 square meters. This probably does not meet most applications requirements, restraining the use of the standard to low data rate traffic.

4. Conclusion

This paper shows that large numbers of simultaneous transmissions should be possible with IEEE 802.15.4A. The Reed-Solomon error correction mechanism has an important effect on performance. These results validate the specification for use in body area networks. Their application requirements often impose small latencies but only require a tiny fraction of the available bandwidth. This greatly reduces the effective number of concurrent transmissions, and combined with the inherent robustness to multi user interference of IR-UWB allows for a high probability of successful packet reception. This is especially important in the envisioned scenarios where several users carrying their own body area network would meet in a single room, or evolve in a crowded environment.

Less favorable results were obtained in the latter case. Near-far interference seems to be a problem when considering large numbers of users. However, in many cases the standard exhibits sufficient robustness.

5. Acknowledgements

The work presented in this paper was supported (in part) by the National Competence Center in Research on Mobile Information and Communication Systems NCCR-MICS, a center supported by the Swiss National Science Foundation under grant number 5005-67322, and by the European Union Pulsers II IST-Project (Contract Number 027142).

References