Ultra wideband technology for wireless sensor networks

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ABSTRACT

Wireless sensor networks (WSNs) have emerged as an important method for planetary surface exploration. To investigate the optimized wireless technology for WSNs, we summarized the key requirements of WSNs and justified ultra wideband (UWB) technology by comparing with other competitive wireless technologies. We also analyzed network topologies as well as physical and MAC layer designs of IEEE 802.15.4a standard, which adopted impulse radio UWB (IR-UWB) technology. Our analysis showed that IR-UWB-based 802.15.4a standard could enable robust communication, precise ranging, and heterogeneous networking for WSNs applications. The result of our present work implies that UWB-based WSNs can be applied to future planetary surface exploration.

Keywords: planetary surface exploration, wireless sensor networks (WSNs), ultra wideband (UWB), impulse radio (IR), IEEE 802.15.4a, low rate (LR), wireless personal area networks (WPANs)

1. INTRODUCTION

Planetary surface exploration is an important aspect of space exploration, the earth surface and other planetary surface (e.g., Moon, Mars) exploration can offer a great deal of meteorological, geological, and biological science return[1][2]. Unlike remote sensing, planetary surface exploration can provide higher spatial resolution and continuous measurements, so it can detect the instant or small-scale events (e.g., small volume of biological gas) Traditional planetary surface exploration relies on single or several non-coordinated high-complexity discrete devices (e.g., lander, rover). However, information about spatio-temporal dynamics information cannot be acquired with this method. Moreover, the system robustness is weak due to less redundancy. Comparing with traditional exploration methods, wireless sensor networks (WSNs)[3][8] use large number spatially distributed low-complexity nodes to coordinately extract spatio-temporal dynamics, provide better robustness, and realize long-term continuous in situ monitoring and exploration. Therefore, WSNs can augment remote sensing and lander/rover method by providing crucial ground-truth and calibration data. However, the severe constraints of WSNs make it hard for existing mature wireless technologies to satisfy its key requirements.

In recent years, ultra wideband (UWB) technology[9][15] has drawn great interest in communication, localization, and radar field. Particularly, Impulse radio UWB (IR-UWB) technology is inherently different from traditional narrowband and wideband technology, it provides high time resolution which enabling high-accuracy ranging[16], multipath fading and jamming resistant[12][17], extremely low power density which makes them coexist with other systems peacefully[18][19], low complexity, small volume, light mass, and low energy consumption[20]. All these appealing properties make IR-UWB as an enabling technology for wireless sensor networks (WSNs) applications[21][24].

In this study, we summarized the key requirements of WSNs and then justified UWB technology by comparison with other competitive wireless technologies. We also analyzed IEEE 802.15.4a standard[25], which adopted IR-UWB technology, with respect to network topologies, physical and MAC layer designs. Our analysis showed that IR-UWB-based 802.15.4a standard could enable robust communication, precise ranging, and heterogeneous networking for WSNs applications. The result of our present work implies that UWB is a enable wireless technology for WSNs application and it can work together with IEEE 802.15.4-2006 MAC layer standard[26] and ZigBee Alliance upper layers standard[27] to realize a complete system solution which will be applied to future planetary surface exploration.

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2. REQUIREMENTS OF WIRELESS SENSOR NETWORKS AND SUITABILITY OF UWB

2.1 Requirements of wireless sensor networks

Wireless sensor networks\(^{[28]-[31]}\) are widely used to measure environmental conditions, such as temperature, pressure, magnetic field, and gravity. In planetary surface exploration, the sensor nodes have to operate under severe constraints on energy consumption, volume, and mass. In addition to these constraints, planetary surface exploration generally does not require real-time data transfer but has more emphasis on the high-accuracy dating and location information of the data\(^{[32]}\). However, there is no global positioning system (GPS) for other planets, and it is costly for every node installing a GPS receiver for the earth surface exploration. The key requirements of WSNs are:

- **Low energy consumption**: WSNs usually have to work for several years without charging or changing battery, this requires extremely low energy consumption of nodes.
- **High robustness**: Wireless channel features are site-specific, robust communication can guarantee quality of service (QoS) under different interference, multipath fading, and shadowing.
- **High-accuracy localization**: In most cases, the sensing data without location information is meaningless. High-accuracy localization also can assist mobile nodes navigation to avoid collision, carters, and obstacles. Besides, high-accuracy localization information can optimize routing to improve efficiency and robustness.
- **Low cost, small volume and light mass**: Large number of nodes makes low cost necessary. The volume and mass of nodes are severely limited so that they can be easily transported and deployed in planetary surface exploration.
- **Heterogeneous networking**: Most WSNs are heterogeneous, where some nodes have more processing ability and energy resource while others have limited complexity and power consumption.
- **Coexistence with other systems**: It is important to guarantee that WSNs will not interference other wireless systems working in the same area.

2.2 Suitability of UWB

In recent years, several existing wireless technologies have been used in WSNs applications. The most widely used IEEE 802.15.4 standard adopts narrowband direct-sequence spread spectrum (DSSS) or parallel sequence spread spectrum (PSSS) PHY along with carrier sense multiple access with collision avoidance (CSMA/CA) MAC layer. Another candidate technology for WSNs is various forms of IEEE 802.11 or Wifi\(^{[33]}\) which is more mature and has been widely adopted in wireless local-area networks (WLAN) applications. IEEE 802.15.1 or Bluetooth\(^{[34]}\) technology has also been adopted in several WSNs applications. UWB technology, especially IR-UWB adopted by IEEE 802.15.4a standard, is inherently different from that in 802.15.4, 802.11, and 802.15.1 standards. It can offer significant advantage with respect to energy consumption, robustness, localization accuracy, cost, volume, mass, and coexistence with other systems. These advantages satisfy almost all the key requirements for WSNs discussed in Section 2.1. Furthermore, the heterogeneous networking requirement has been fulfilled by IR-UWB-based specification in IEEE 802.15.4a standard which will be discussed in detail in Section 3. Comparison of these four standards is given in Table 1 which clearly demonstrates the suitability of UWB for WSNs applications. Short transmission distance issue of UWB can be mitigated in WSNs by multi-hop relay and cooperative technology\(^{[35][36]}\).

<table>
<thead>
<tr>
<th>Key Requires for WSNs</th>
<th>IEEE 802.15.4</th>
<th>IEEE 802.11</th>
<th>IEEE 802.15.1</th>
<th>IEEE 802.15.4a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy consumption</td>
<td>Low, 20mW-40mW</td>
<td>High, 500mW-1W</td>
<td>Medium, 40-100mW</td>
<td>Low, 30mW</td>
</tr>
<tr>
<td>Robustness</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Localization accuracy</td>
<td>Low, several meters</td>
<td>Low, several meters</td>
<td>Low, several meters</td>
<td>High, &lt; 1 meter</td>
</tr>
<tr>
<td>Cost, volume, mass</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Heterogeneous networking</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Coexistence with other systems</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Data rate</td>
<td>250kb/s for 2.4GHz band</td>
<td>24Mb/s for 802.11a</td>
<td>1Mb/s</td>
<td>851b/s (mandatory)</td>
</tr>
<tr>
<td>Transmission distance</td>
<td>Medium, &lt; 30 meters</td>
<td>Long, &lt; 100 meters</td>
<td>Short, &lt;10 meters</td>
<td>Medium, &lt; 70 meters</td>
</tr>
</tbody>
</table>

3. IEEE 802.15.4A STANDARD

In March 2004, the IEEE 802.15.4a task group (TG4a) was created to develop alternative physical layer (PHY) for low rate (LR) wireless personal area networks (WPANs) applications such as WSNs. IEEE 802.15.4a standard, which is an
amendment to the popular IEEE 802.15.4-2006 standard, provides new options for PHY to support higher data rates, extended range, improved robustness, precise ranging, and heterogeneous networking. It was approved in March 2007 and published in June 2007. IEEE 802.15.4a standard specifies two optional signaling formats: IR-UWB and chirp spread spectrum (CSS), and we focus our discussion on the former.

3.1 Network topologies
IEEE 802.15.4a supports all types of topologies and devices defined by the IEEE 802.15.4 standard[37][38]. There are two basic types of network topologies: star topology and peer-to-peer topology as shown in Figure 1. The devices in the Figure are divided into two classes: full function devices (FFDs), which implement complex function such as wireless channel control, and reduced function devices (RFDs), which only implement simple function such as measuring physical parameters. FFDs and RFDs organize themselves to form personal area networks (PANs), which are usually heterogeneous networks. An FFD is commonly referred to as a “PAN coordinator” due to its ability to coordinate the entire PAN.

In star topology, FFDs and RFDs can only exchange information with the PAN coordinator. In peer-to-peer topology, FFDs can communicate with each other directly as long as they are within physical reach, while RFDs can only exchange information with FFDs. The topology choosing is determined by the requirements of application. Star topology offers low latency and is easier to implement, while peer-to-peer topology can form complex network formations, such as mesh, tree, cluster, and cluster-tree, and the resulting networks can be ad hoc, self-organizing, and self-healing.

![Star Topology](image1.png)

![Peer-to-Peer Topology](image2.png)

Figure 1. Star and peer-to-peer network topologies.

3.2 PHY design
3.2.1 Band plan
The UWB PHY supports 16 channels which located in three independent bands: the sub-gigahertz band, the lower band, and the higher band, as listed in Table 2.

<table>
<thead>
<tr>
<th>Channel Number</th>
<th>Band</th>
<th>Center Freq. (MHz)</th>
<th>Bandwidth (MHz)</th>
<th>Mandatory</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Sub-GHz</td>
<td>499.2</td>
<td>499.2</td>
<td>Yes</td>
</tr>
<tr>
<td>1</td>
<td>Low band</td>
<td>3494.4</td>
<td>499.2</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>Lower band</td>
<td>3993.6</td>
<td>499.2</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>Low band</td>
<td>4492.8</td>
<td>499.2</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>Low band</td>
<td>3993.6</td>
<td>1331.2</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>High band</td>
<td>6498.6</td>
<td>499.2</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>High band</td>
<td>6988.8</td>
<td>1018.6</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>High band</td>
<td>6498.6</td>
<td>1018.6</td>
<td>No</td>
</tr>
</tbody>
</table>

Several band plan considerations are summarized below:
- There is one mandatory channel in each band and a compliant device should support at least one mandatory channel.
• The bandwidth is about 500 MHz except channel \{4, 7, 11, 15\}, the bandwidth of these channels are larger than 1 GHz. Larger bandwidth increase the transmitted power under regulation, and it allows higher time resolution resulting higher accurate range estimate. On the other hand, larger bandwidth poses challenges to transceiver design as well as its power consumption and cost.
• The bands are chosen to avoid the 5 GHz industrial, scientific and medical (ISM) bands in an attempt to avoid interference and overcrowding.
• The center frequency of each channel can be derived from a variety of readily available crystal oscillators.

3.2.2 Channel models

For system standardization, site-independent channel models are required to serve as a reference that is used for comparison of different system proposals through simulation. IEEE 802.15.4a channel models\(^39\) are summarized below:
• For the frequency range from 2 to 10 GHz, the channel models parameterized indoor residential, indoor office, industrial, outdoor, and open outdoor environments (usually with a distinction between line-of-sight (LOS) and non-line-of-sight (NLOS) properties).
• Some of the environments (industrial NLOS, office NLOS) use a dense channel model with a “soft onset” of the power delay profile\(^40\), while others use a generalized Saleh-Valenzuela (SV) model\(^41\).
• There is a model for body area networks (BANs) and the frequency range of this model is from 2 to 6 GHz.
• For the frequency range from 100 to 900 MHz, it gives a model for indoor office-type environments.
• The 802.15.4a model is more general and based on more measurements than the earlier 802.15.3a model and both channel models are suitable for simulation of UWB systems with arbitrary data rates and modulations.

3.2.3 Coding and modulation

In order to enable heterogeneous networking which is a key requirement of WSNs as discussed in Section 2.1, the modulation, multiple access schemes (MCM), and coding have been designed to allow the FFDs to employ coherent reception resulting enhanced performance at the cost of energy consumption and complexity, while RFDs use simple noncoherent receivers (energy detectors) for reduced current drain and design simplicity.

A hybrid modulation\(^42\) that combines burst position modulation (BPM) and binary phase shift keying (BPSK) is used to support both coherent and noncoherent receivers using a common signaling scheme:

\[
w^{(k)}(t) = \sum_{i} b_i^{(k)} s_i^{(k)}(t - iT_s - b_T^{(k)}T_{BPM} - c_i^{(k)}T_b); s_i^{(k)}(t) = \sum_{n=0}^{N-1} p(t - nT_c)d_{i,n}^{(k)}
\]  

(1)

where\(^\dagger\): superscript \(^{(k)}\) denotes the \(k\)th user; \(b_i^{(k)}\) is the \(i\)th data bit to be transmitted; \(\tilde{b}_i^{(k)}\) is the parity check bit associated with the \(i\)th data bit; \(s_i^{(k)}(t)\) is one burst waveform which consists \(N\) = 16 pulses; \(p(t)\) is the “basis pulse” that has to have a correlation with a raised-cosine pulse of better than 0.8\(^\ddagger\); \(T_c\) is the chip duration of approximately 2 ns; \(T_b\) is the burst-hopping duration, which equals \(T_c = NT_c = 32\) ns; \(T_{BPM}\) is the burst position modulation interval, which equals \(T_{BPM} = 16T_b = 512\) ns; \(T_c\) is the symbol duration, which equals \(T_s = 2T_{BPM} = 1024\) ns; \(c_i^{(k)}\) is the time-hopping sequence for multiuser access; \(d_{i,n}^{(k)}\) is a pseudorandom scrambling sequence drawn from \(\{1, -1\}\).

One example of this modulation scheme is depicted in Figure 2, where the shadowed part is one burst of pulses. Several features of the modulation and MCM schemes are summarized below:
• The modulation interval \(T_{BPM}\) = 512 ns is chosen much larger than the typical channel delay spreads, so that a noncoherent receiver can detect the BPM even in channels with heavy delay dispersion.
• The duration of the burst waveform is on the order of, or shorter than, typical channel delay spreads, so shortening the duration of the burst waveform would not significantly reduce the optimum integration duration of noncoherent receiver.
• A coherent receiver can perform a correlation with \(s_i^{(k)}(t)\), and thus enhanced the signal-to-noise ratio (SNR) by a factor of \(N\) with respect to a noncoherent receiver.

\(^\dagger\) Parameters discussed in this paper are for the mandatory 851 kb/s mode operating at a 16 MHz average pulse repletion frequency.
\(^\ddagger\) Alternative pulse shapes have also been defined in the standard to improve multiple access and reduce interference.
For both noncoherent and coherent receiver, the signal format provides time hopping (TH) MCM, so the performance of FFDs with this flexible MCM is almost as good as with an MCM that is designed for homogeneous coherent-receiver networks.

The maximum time shift is $8T_b$, so a guard interval $8T_b = 256$ ns is used to against heavy delay dispersion channels.

Since the pseudorandom scrambling sequence $d_{(k)}^{(s)}$ is different for different users, it provides multi-access interference suppression for coherent receivers through matched filtering.

The UWB PHY supports an over-the-air mandatory data rate of 851 kb/s with optional data rates of 110 kb/s, 6.81 Mb/s, and 27.24 Mb/s, and the various data rates are supported through the change of the bursts length $N$.

The coherent receivers can receive two bits per symbol, while noncoherent receivers can only receive one bit. The use of additional bit $\hat{b}$ will be discussed in the following coding part in this section.

Figure 2. Modulation and time-hopping of the 802.15.4a standard Frame format.

In WSNs applications, the coherent and noncoherent receivers should get the same information. Because:

- Coherent and noncoherent receivers should get the same information during multicast/broadcast transmissions.
- Relay nodes often are noncoherent receivers even if the ultimate destination of the message is a coherent receiver.

Therefore, the additional bit for coherent receiver discussed above should be used to provide higher coding gain to improve the robustness rather than convey information. A systematic RS-Convolution concatenated code is used in the standard, in which the information bits are transmitted unchanged along with the parity check bits. The systematic bits are used to determine the position of the burst, and are thus available to both noncoherent and coherent receivers. The parity bits are modulated onto the burst phase and are thus available only to coherent receivers. A block diagram of IEEE 802.15.4a coding scheme is provided in Figure 3. This coding scheme allows one to implement a variety of decoders that have different tradeoffs between complexity and performance, such as no decoding, hard decoding, soft decoding, and turbo-decoding.

Figure 3. IEEE 802.15.4a coding scheme.

### 3.2.4 Frame format

In IEEE 802.15.4a networks, devices communicate using the packet format illustrated in Figure 4. Each packet, or PHY protocol data unit (PPDU), contains a synchronization header (SHR) preamble, a PHY header (PHR), and a data field, or PHY service data unit (PSDU). The SHR preamble is composed of a preamble and a start-of-frame delimiter (SFD).

The functionalities of preamble are acquisition, synchronization, channel sounding, and leading edge detection. In 802.15.4a, perfectly balanced ternary sequences (PBTS) \cite{43,44} which have perfect autocorrelation feature are used as the
basis preamble symbol set. The 802.15.4a standard uses length-31 or length-127 PBTS, the length-31 PBTS adopted in the standard is listed in Figure 5. The preamble uses a large number of repetitions of the PBTS to improve SNR via processing gain; the resulting high SNR signal and its perfect autocorrelation feature is thus well suited for channel estimation and leading edge detection. The autocorrelation of three-times-repeating S1 with S1 itself is illustrated in Figure 5, the central part of the figure displays the perfect periodic autocorrelation peaks with no side-lobes between them, while nonzero side-lobes at the beginning and end are due to transient effects.

As illustrated in Figure 4, SFD is added prior to the PHR, it is used to perform frame synchronization and ranging counter management. The standard specifies a long and a short SFD, the short SFD consists of 8 preamble symbols and is used for all data rate $\geq 0.8$ Mb/s, whereas the long SFD is 64 symbols long and is used for the lowest data rate. Processing gain for detection of the SFD is 6 dB higher than that for an individual preamble symbol, so the detection of SFD plays an important part in accurate ranging which will be discussed in following Section 3.2.5.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{IEEE_802.15.4a_frame_format.png}
\caption{IEEE 802.15.4a frame format.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{basis_preamble_symbol_set.png}
\caption{The basis preamble symbol set and periodic autocorrelation of S1.}
\end{figure}

3.2.5 Ranging

UWB networks typically use time-of-arrival (ToA) for determining the range between different nodes; those ranges form the basis of the actual location estimation\cite{12,21,45}. Furthermore, two-way (TW) ranging protocol is widely used in WSNs applications, since it avoids accurate time synchronization of network. In the standard, only the ranging protocol is defined, the algorithm and implementation of signal detection and range estimation are not specified. For general discussion on range estimation technologies, we refer the reader to the reference\cite{12,46}.

In TW ranging protocol as illustrated in Figure 6, an original ranging node A, RDEV A, first transmits a signal called range request packet (RFRAME\textsubscript{REQ}) to a target ranging node B, RDEV B. Considering the higher processing gain feature of SFD discussed in section 3.2.4, SFD detection instants offer better accuracy to manage timing counters. Therefore, on detection of the SFD of RFRAME\textsubscript{REQ}, the ranging timing counter of RDEV B is started. After reception of the RFRAME\textsubscript{REQ}, RDEV B prepares and sends an acknowledgment packet, also called range reply packet (RFRAME\textsubscript{REP}),
back to node A. Similarly, the time instant that the SFD of RFRAMEREP leaves the transmit antenna, the ranging timing counter of RDEV B is stopped. The difference in these two counter values corresponds to the turnaround time $T_{ta}^B$. In a separate packet called time stamp report, RDEV B reports to RDEV A the turnaround time. Node A can determine the total round-trip time $T_{round}^A$ in a similar way, and then it can compute the range using:

$$T_{round}^A = T_{round}^A - T_{ta}^B \over 2$$

(2)

In order to minimize range errors of TW ranging protocol due to clock frequency offset, a symmetric double-sided ranging protocol[14][47] was introduced. In order to against network attacks, IEEE 802.15.4a standard provides a “private ranging” mode[48]. In this mode, the ranging is provisioned in two steps: authentication and ranging, and the ranging preamble uses length-127 PBTS.

Figure 6. Two-way ranging protocol.

3.3 MAC design

According to IEEE 802.15.4a specification, different networks are distinguished by using different frequency bands and different codes (PBTS sequences for the preambles, burst-hopping codes, and scrambling codes). Within an IEEE 802.15.4a network, ALOHA channel access is adopted. This is based on the multi-user interference (MUI) robustness guaranteed by the UWB PHY that enables the ALOHA approach to provide satisfactory throughput in medium and lightly loaded networks, avoiding the additional access delay due to the collision avoidance phase. For star topology, beacon-based transmission using superframes and guaranteed time slots (GTSs) (Figure 7(a)) can be used. For peer-to-peer topology, devices adopt a carrier sense multiple access with collision avoidance (CSMA/CA) protocol to access the medium. A TDMA-type multiplexed preamble scheme that enables preamble-detection-based clear channel assessment (CCA) for UWB systems are developed[49] as illustrated in Figure 7(b). In this scheme, preamble symbols are multiplexed with the IEEE 802.15.4 packet by periodically inserting them into the header and payload parts of the packet after every k-symbol-long interval.

Figure 7. (a) Superframe structure with GTSs; (b) TDMA-style multiplexed preamble to support CCA.
4. CONCLUSION

In this paper, we analyzed the key requirements of WSNs and justified the suitability of UWB technology. Conclusions derived from our design issue discussions of IEEE 802.15.4a standard showed its ability to enable robust communication, precise ranging, and heterogeneous networking for WSNs applications. The 802.15.4a standard is specially designed to work with the IEEE 802.15.4-2006 MAC standard as well as the ZigBee Alliance upper layer specification to realize a complete system solution. The commercialization of 802.15.4a-compliant devices has already begun[50]. It is expected that the 802.15.4a-based solution will be adopted in future planetary surface exploration as well as many other areas.

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REFERENCES


