A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi

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Abstract

Bluetooth (over IEEE 802.15.1), ultra-wideband (UWB, over IEEE 802.15.3), ZigBee (over IEEE 802.15.4), and Wi-Fi (over IEEE 802.11) are four protocol standards for short range wireless communications with low power consumption. From an application point of view, Bluetooth is intended for a cordless mouse, keyboard, and hands-free headset, UWB is oriented to high-bandwidth multimedia links, ZigBee is designed for reliable wirelessly networked monitoring and control networks, while Wi-Fi is directed at computer-to-computer connections as an extension or substitution of cabled networks. In this paper, we provide a study of these popular wireless communication standards, evaluating their main features and behaviours in terms of various metrics, including the transmission time, data coding efficiency, complexity, and power consumption. It is believed that the comparison presented in this paper would benefit application engineers in selecting an appropriate protocol.

Index Terms: Wireless protocols, Bluetooth, ultra-wideband (UWB), ZigBee, Wi-Fi, short-range communications.

1. Introduction

The short-range wireless scene is currently held by four protocols: the Bluetooth, and UWB, ZigBee, and Wi-Fi, which are corresponding to the IEEE 802.15.1, 802.15.3, 802.15.4, and 802.11a/b/g standards, respectively. IEEE defines the physical (PHY) and MAC layers for wireless communications over an action range around 10-100 meters. For Bluetooth and Wi-Fi, Ferro and Potortí compared their main features and
behaviors in terms of various metrics, including capacity, network topology, security, quality of service support, and power consumption. In Wang et al. compared the MAC of IEEE 802.11e and IEEE 802.15.3. Their results showed that the throughput difference between them is quite small. In addition, the power management of 802.15.3 is easier than that of 802.11e. For ZigBee and Bluetooth, Baker studied their strengths and weaknesses for industrial applications, and claimed that ZigBee over 802.15.4 protocol can meet a wider variety of real industrial needs than Bluetooth due to its long term battery operation, greater useful range, flexibility in a number of dimensions, and reliability of the mesh networking architecture.

In this paper, after an overview of the mentioned four short range wireless protocols, we attempt to make a preliminary comparison of them and then specifically study their transmission time, data coding efficiency, protocol complexity, and power consumption. The rest of this paper is organized as follows. Section 2 briefly introduces the wireless protocols including Bluetooth, UWB, ZigBee, and Wi-Fi. Next, a comprehensive evaluation of them is described in Section 3. Then, in Section 4, the complexity and power consumption are compared based on IEEE standards and commercial off the-shelf wireless products, respectively. Finally, Section 5 concludes this paper.

2. Wireless Protocols

This section introduces the Bluetooth, UWB, ZigBee, and Wi-Fi protocols, which corresponds to the IEEE 802.15.1, 802.15.3, 802.15.4, and 802.11a/b/g standards, respectively. The IEEE defines only the PHY and MAC layers in its standards. For each protocol, separate alliances of companies worked to develop specifications covering the network, security and application profile layers so that the commercial potential of the standards could be realized. The material presented in this section is widely available in the literature. Hence, the major goal of this paper is not to contribute to research in the area of wireless standards, but to present a comparison of the four main short-range wireless networks.

2.1 Bluetooth over IEEE 802.15.1

Bluetooth, also known as the IEEE 802.15.1 standard is based on a wireless radio system designed for short-range and cheap devices to replace cables for computer peripherals, such as mice, keyboards, joysticks, and printers. This range of applications is known as wireless personal area network (WPAN). Two connectivity topologies are defined in Bluetooth: the piconet and scatternet. A piconet is a WPAN formed by a Bluetooth device serving as a master in the piconet and one or more Bluetooth devices serving as slaves. A frequency-hopping channel based on the address of the master defines each piconet. All devices participating in communications in a given piconet are synchronized using the clock of the master. Slaves communicate only with their master in a point-to-point fashion under the control of the master. The master’s transmissions may be either point-to-point or point-to-multipoint. Also, besides in an active mode, a slave device can be in the parked or standby modes so as to reduce power consumptions. A scatternet is a collection of operational Bluetooth piconets overlapping in time and space. Two piconets can be connected to form a scatternet. A
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Bluetooth device may participate in several piconets at the same time, thus allowing for the possibility that information could flow beyond the coverage area of the single piconet. A device in a scatternet could be a slave in several piconets, but master in only one of them.

2.2. UWB over IEEE 802.15.3

UWB has recently attracted much attention as an indoor short-range high-speed wireless communication. One of the most exciting characteristics of UWB is that its bandwidth is over 110 Mbps (up to 480 Mbps) which can satisfy most of the multimedia applications such as audio and video delivery in home networking and it can also act as a wireless cable replacement of high speed serial bus such as USB 2.0 and IEEE 1394. Following the United States and the Federal Communications Commission (FCC) frequency allocation for UWB in February 2002, the Electronic Communications Committee (ECC TG3) is progressing in the elaboration of a regulation for the UWB technology in Europe. From an implementation point of view, several solutions have been developed in order to use the UWB technology in compliance with the FCC’s regulatory requirements. Among the existing PHY solutions, in IEEE 802.15 Task Group 3a (TG3a), multiband orthogonal frequency-division multiplexing (MB-OFDM), a carrier-based system dividing UWB bandwidth to sub-bands, and direct-sequence UWB (DS-UWB), an impulse-based system that multiplies an input bit with the spreading code and transmits the data by modulating the element of the symbol with a short pulse have been proposed by the WiMedia Alliance and the UWB Forum, respectively. The TG3a was established in January 2003 to define an alternative PHY layer of 802.15.3. However, after three years of a jammed process in IEEE 802.15.3a, supporters of both proposals, MB-OFDM and DS-UWB, supported the shut down of the IEEE 802.15.3a task group without conclusion in January 2006. On the other hand, IEEE 802.15.3b, the amendment to the 802.15.3 MAC sublayer has been approved and released in March 2006.

2.3. ZigBee over IEEE 802.15.4

ZigBee over IEEE 802.15.4, defines specifications for lowrate WPAN (LR-WPAN) for supporting simple devices that consume minimal power and typically operate in the personal operating space (POS) of 10m. ZigBee provides self-organized, multi-hop, and reliable mesh networking with long battery lifetime. Two different device types can participate in an LR-WPAN network: a full-function device (FFD) and a reduced function device (RFD). The FFD can operate in three modes serving as a PAN coordinator, a coordinator, or a device. An FFD can talk to RFDs or other FFDs, while an RFD can talk only to an FFD. An RFD is intended for applications that are extremely simple, such as a light switch or a passive infrared sensor. They do not have the need to send large amounts of data and may only associate with a single FFD at a time. Consequently, the RFD can be implemented using minimal resources and memory capacity. After an FFD is activated for the first time, it may establish its own network and become the PAN coordinator. All star networks operate independently
from all other star networks currently in operation. This is achieved by choosing a PAN identifier, which is not currently used by any other network within the radio sphere of influence. Once the PAN identifier is chosen, the PAN coordinator can allow other devices to join its network. An RFD may connect to a cluster tree network as a leave node at the end of a branch, because it may only associate with one FFD at a time. Any of the FFDs may act as a coordinator and provide synchronization services to other devices or other coordinators. Only one of these coordinators can be the overall PAN coordinator, which may have greater computational resources than any other device in the PAN.

2.4. Wi-Fi over IEEE 802.11a/b/g
Wireless fidelity (Wi-Fi) includes IEEE 802.11a/b/g standards for wireless local area networks (WLAN). It allows users to surf the Internet at broadband speeds when connected to an access point (AP) or in ad hoc mode. The IEEE 802.11 architecture consists of several components that interact to provide a wireless LAN that supports station mobility transparently to upper layers. The basic cell of an IEEE 802.11 LAN is called a basic service set (BSS), which is a set of mobile or fixed stations. If a station moves out of its BSS, it can no longer directly communicate with other members of the BSS. Based on the BSS, IEEE 802.11 employs the independent basic service set (IBSS) and extended service set (ESS) network configurations. The IBSS operation is possible when IEEE 802.11 stations are able to communicate directly without any AP. Because this type of IEEE 802.11 LAN is often formed without pre-planning, for only as long as the LAN is needed, this type of operation is often referred to as an ad hoc network. Instead of existing independently, a BSS may also form a component of an extended form of network that is built with multiple BSSs. The architectural component used to interconnect BSSs is the distribution system (DS). The DS with APs allow IEEE 802.11 to create an ESS network of arbitrary size and complexity. This type of operation is often referred to as an infrastructure network.

3. Comparative Study
Table 1 summarizes the main differences among the four protocols. Each protocol is based on an IEEE standard. Obviously, UWB and Wi-Fi provide a higher data rate, while Bluetooth and ZigBee give a lower one. In general, the Bluetooth, UWB, and ZigBee are intended for WPAN communication (about 10m), while Wi-Fi is oriented to WLAN (about 100m). However, ZigBee can also reach 100m in some applications. FCC power spectral density emission limit for UWB emitters operating in the UWB band is -41.3 dBm/Mhz. This is the same limit that applies to unintentional emitters in the UWB band, the so called Part 15 limit. The nominal transmission power is 0 dBm for both Bluetooth and ZigBee, and 20 dBm for Wi-Fi.
Table 1: Comparison of the Bluetooth, UWB, Zigbee, And Wi-Fi Protocols.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Bluetooth</th>
<th>UWB</th>
<th>Zigbee</th>
<th>Wi-Fi</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE spec.</td>
<td>802.15.1</td>
<td>802.15.3a</td>
<td>802.15.4</td>
<td>802.11a/b/g</td>
</tr>
<tr>
<td>Frequency band</td>
<td>2.4GHz</td>
<td>3.1-10.6 GHz</td>
<td>868/915 MHz; 2.4 GHz</td>
<td>2.4 GHz; 5 GHz</td>
</tr>
<tr>
<td>Max signal rate</td>
<td>1 Mb/s</td>
<td>110Mb/s</td>
<td>250kb/s</td>
<td>54Mb/s</td>
</tr>
<tr>
<td>Nominal range</td>
<td>10 m</td>
<td>10 m</td>
<td>10-100 m</td>
<td>100 m</td>
</tr>
<tr>
<td>Nominal TX power</td>
<td>0 - 10 dBm</td>
<td>-41.3 dBm/MHz</td>
<td>(-25) - 0 dBm</td>
<td>15 - 20 dBm</td>
</tr>
<tr>
<td>Number of RF</td>
<td>79 (1-15)</td>
<td>1/10;16</td>
<td>14(2.4GHz)</td>
<td></td>
</tr>
<tr>
<td>channels</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>1MHz</td>
<td>500MHz-7.5GHz</td>
<td>0.3/0.6 MHz; 2 MHz</td>
<td>22MHz</td>
</tr>
<tr>
<td>Modulation type</td>
<td>GFSK</td>
<td>BPSK, QPSK</td>
<td>BPSK (+ ASK), O-QPSK</td>
<td>BPSK, QPSK, COFDM, CCK, M-QAM</td>
</tr>
<tr>
<td>Spreading</td>
<td>FHSS</td>
<td>DS-UWB, MB-OFDM</td>
<td>DSSS</td>
<td>DSSS, CCK, OFDM</td>
</tr>
<tr>
<td>mechanism</td>
<td>hopping</td>
<td>hopping</td>
<td>selection transmit</td>
<td>transmit power control</td>
</tr>
<tr>
<td>Basic cell</td>
<td>Piconet</td>
<td>Piconet</td>
<td>Star</td>
<td>BSS</td>
</tr>
<tr>
<td>Extension of the</td>
<td>Scatternet</td>
<td>Peer-peer</td>
<td>Cluster tree-mesh</td>
<td>ESS</td>
</tr>
<tr>
<td>basic cell</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max number of</td>
<td>8</td>
<td>8</td>
<td>&gt; 65000</td>
<td>2007</td>
</tr>
<tr>
<td>cell nodes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data protection</td>
<td>16-bit CRC</td>
<td>32-bit CRC</td>
<td>16-bit CRC</td>
<td>32-bit CRC</td>
</tr>
</tbody>
</table>

3.1 Radio Channels
Bluetooth, ZigBee and Wi-Fi protocols have spread spectrum techniques in the 2.4 GHz band, which is unlicensed in most countries and known as the industrial, scientific, and medical (ISM) band. Bluetooth uses frequency hopping (FHSS) with 79 channels and 1 MHz bandwidth, while ZigBee uses direct sequence spread spectrum (DSSS) with 16 channels and 2 MHz bandwidth. Wi-Fi uses DSSS (802.11), complementary code keying (CCK, 802.11b), or OFDM modulation (802.11a/g) with 14 RF channels (11 available in US, 13 in Europe, and just 1 in Japan) and 22 MHz bandwidth. UWB uses the 3.1-10.6 GHz, with an unapproved and jammed 802.15.3a standard, of which two spreading techniques, DSUWB and MB-OFDM, are available.
3.2 Network Size
The maximum number of devices belonging to the network’s building cell is 8 (7 slaves plus one master) for a Bluetooth and UWB piconet, over 65000 for a ZigBee star network, and 2007 for a structured Wi-Fi BSS. All the protocols have a provision for more complex network structures built from the respective basic cells: the scatternet for Bluetooth, peer-to-peer for UWB, cluster tree or mesh networks for ZigBee, and the ESS for Wi-Fi.

3.3 Security
All the four protocols have the encryption and authentication mechanisms. Bluetooth uses the E0 stream cipher and shared secret with 16-bit cyclic redundancy check (CRC), while UWB and ZigBee adopt the advanced encryption standard (AES) block cipher with counter mode (CTR) and cipher block chaining message authentication code (CBC-MAC), also known as CTR with CBC-MAC (CCM), with 32-bit and 16-bit CRC, respectively. In 802.11, Wi-Fi uses the RC4 stream cipher for encryption and the CRC-32 checksum for integrity. However, several serious weaknesses were identified by cryptanalysts, any wired equivalent privacy (WEP) key can be cracked with readily available software in two minutes or less, and thus WEP was superseded by Wi-Fi protected access 2 (WPA2), i.e. IEEE 802.11i standard, of which the AES block cipher and CCM are also employed.

3.4. Transmission Time
The transmission time depends on the data rate, the message size, and the distance between two nodes. The formula for transmission time ($\mu$s) can be described as:

$$T_{tx} = (N_{data} + (N_{data} / N_{maxPld} \cdot N_{ovhd})) \cdot T_{bit} + T_{prop}$$

where $N_{data}$ is the data size, $N_{maxPld}$ is the maximum payload size, $N_{ovhd}$ is the overhead size, $T_{bit}$ is the bit time, and $T_{prop}$ is the propagation time between any two devices. For simplicity, the propagation time is negligible. Note that the maximum data rate 110 Mbit/s of UWB is adopted from an unapproved 802.15.3a standard. The transmission time for the ZigBee is longer than the others because of the lower data rate (250 Kbit/s), while UWB requires less transmission time compared with the others. Obviously, the result also shows the required transmission time is proportional to the data payload size and disproportional to the maximum data rate.

3.5 Power Consumption
Bluetooth and ZigBee are intended for portable products, short ranges, and limited battery power. Consequently, it offers very low power consumption and, in some cases, will not measurably affect battery life. UWB is proposed for shortrange and high data rate applications. On the other hand, Wi-Fi is designed for a longer connection and supports devices with a substantial power supply. Obviously, the Bluetooth and ZigBee protocols consume less power as compared with UWB and Wi-Fi. Based on the bit rate, a comparison of normalized energy consumption is provided in Fig. 1. From the mJ/Mb unit point of view, the UWB and Wi-Fi have better efficiency in
energy consumption. In summary, Bluetooth and ZigBee are suitable for low data rate applications with limited battery power (such as mobile devices and battery-operated sensor networks), due to their low power consumption leading to a long lifetime. On the other hand, for high data rate implementations (such as audio/video surveillance systems), UWB and Wi-Fi would be better solutions because of their low normalized energy consumption.

![Comparison of the normalized energy consumption for each protocol.](image)

**Fig. 1:** Comparison of the normalized energy consumption for each protocol.

4. Conclusions
This paper has presented a broad overview of the four most popular wireless standards, Bluetooth, UWB, ZigBee, and Wi-Fi with a quantitative evaluation in terms of the transmission time, data coding efficiency, protocol complexity, and power consumption. Furthermore, the radio channels, coexistence mechanism, network size, and security are also preliminary compared. This paper is not to draw any conclusion regarding which one is superior since the suitability of network protocols is greatly influenced by practical applications, of which many other factors such as the network reliability, roaming capability, recovery mechanism, chipset price, and installation cost need to be considered in the future.

References


