Comparison of the IEEE 802.11, 802.15.1, 802.15.4 and 802.15.6 wireless standards

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1 Introduction

This paper contains a comparison of some of the wireless standards authored by the Institute of Electrical and Electronics Engineers (IEEE) [1]. It explain some of the differences and similarities between the IEEE 802.11, 802.15.1, 802.15.4 and 802.15.6 wireless standards with an emphasis on the physical layer.

2 Wireless standards

The wireless standards that we will investigate in this paper is only a selection from all the standards available. These explanations are not meant to be exhaustive.

2.1 IEEE 802.11 - WLAN/Wi-Fi

Wireless LAN (WLAN, also known as Wi-Fi) is a set of low tier, terrestrial, network technologies for data communication. The WLAN standards operates on the 2.4 GHz and 5 GHz Industrial, Science and Medical (ISM) frequency bands. It is specified by the IEEE 802.11 standard [2] and it comes in many different variations like IEEE 802.11a/b/g/n. The application of WLAN has been most visible in the consumer market where most portable computers support at least one of the variations.

2.2 IEEE 802.15.1 - Bluetooth

The IEEE 802.15.1 standard [3] is the basis for the Bluetooth wireless communication technology. Bluetooth is a low tier, ad hoc, terrestrial, wireless standard for short range communication. It is designed for small and low cost devices with low power consumption. The technology operates with three different classes of devices: Class 1, class 2 and class 3 where the range is about 100 meters, 10 meters and 1 meter respectively. Wireless LAN operates in the same 2.4 GHz frequency band as Bluetooth, but the two technologies use different signaling methods which should prevent interference.

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2.3 IEEE 802.15.4 - ZigBee

ZigBee is a low tier, ad hoc, terrestrial, wireless standard in some ways similar to Bluetooth. The IEEE 802.15.4 standard [4] is commonly known as ZigBee, but ZigBee has some features in addition to those of 802.15.4. It operates in the 868 MHz, 915 MHz and 2.4 GHz ISM bands.

2.4 IEEE 802.15.6

IEEE 802.15.6 is a bit elusive, but some of the available information points to some kind of wireless Body Area Network (BAN). It is possible that it is meant to be the WBAN Study Group Medical Body Area Networks (SG-MBAN), but that group have not yet released any standards. SG-MBAN's meeting minutes from their meeting in Montreal, May 2007 [5] indicates that the group name has not been clarified as one of their members asked if the group title will be 15.5x or 15.6 without getting an answer. This could explain why no standard has been released and little information about the specification could be found. According to their meeting minutes from San Fransisco, July 2007 [6] and the Montreal meeting minutes, the frequency band has not yet been clarified.

A paper by S. Maharj [7] from the University of KwaZulu-Natal is the only reference of frequency and throughput on 802.15.6 I have been able to find. The paper says that 802.15.6 will cover the terahertz range and it will use T-rays which has properties of both light and radio. It also explains that the theoretical maximum data rate will be in the order of several gigabit. Unfortunately the information from this paper does not correspond with what I have read from the meeting minutes of SG-MBAN. However, this is the only concrete information I could locate.

3 Modes of operation

Wireless networks can have to distinct modes of operation: Ad hoc and infrastructured. Infrastructured wireless networks usually have some kind of base station[1] which acts as a central node which connects the wireless terminals. The base station is usually provided in order to enable access to the Internet, an intranet or other wireless networks. Most of the time the base stations have a fixed location, but certain mobile base stations also exist. The disadvantage over ad hoc networks is that the base station is a central point of failure. If it stops working none of the wireless terminals can communicate with each other.

Ad hoc networks can be formed "on the fly" without the help of a base station. Self organization is the key to forming an ad hoc network because initially there is no central node to talk to. In ad hoc networks the wireless terminals may communicate directly with each other while terminals in infrastructured networks has to use the base station to relay their messages.

The different standards have different capabilities when it comes to these two modes of operation. Table 1 contains an overview of which standards support which modes.

[1] In the context of the 802.11 standards it is called an access point (AP).

Standard	Ad hoc	Infrastructured
802.11a/b/g/n	Yes	Yes
802.15.1	Yes	No
802.15.4	Yes	No
802.15.6	Unknown	Unknown

Table 1: Modes of operation for the different wireless standards

4 Medium access

In order to conduct two-way wireless communication a protocol detailing how the wireless terminals are to access this medium must be established. The 802.11 standard specifies a method called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Carrier Sense Multiple Access with Collision Detection (CSMA/CD) used by Ethernet is the wired counterpart to CSMA/CA. The CSMA/CA technique allows wireless transmissions to be completed without interference from other terminals.

When CSMA/CA is used a part of the potential data rate is lost to the overhead of this protocol. If the communication was one-way only the communication channels could be better utilized because the source terminal would not have to take into consideration transmissions being sent from other terminals. In order to deal with the hidden terminal problem 802.11 can also use a request to send, clear to send (RTS/CTS) scheme in order to reserve the channel for communication.

5 Frequency, data rate and range

The standards described earlier differ by which frequencies they use and this affects the data rate and range they can cover. According to Table 2 802.15.6 (BAN) will have a much shorter range than the other technologies, but this proves to be an advantage. Shorter range communication has lower power requirements, enables equipment to be smaller and the potential for frequency reuse is very good. This is good news for BAN since it is designed to be as unobtrusive as possible by integration into clothing, attached to the body or as implants.

From the table you can also see that several of the standards operate in the 2.4 GHz band. 802.11g is designed so that it is compatible with 802.11b so that they can co-exist. However, when a 802.11g base station operates in 802.11b mode its data rate is reduced to that of 802.11b for all its connected terminals. 802.15.1 also occupies the 2.4 GHz band, but a different signaling method can be used so that they don't suffer too badly from interference. Along with these two standards we also have common household appliances like microwave ovens and certain wireless phones which might pollute the 2.4 GHz frequency spectrum.

One observation from Table 2 is that 802.11n can have a data rate as high as 248 Mbps in the same frequency band as the other standards. The major large in increase in data rate and range is achieved by using technique called Multiple-Input Multiple-Output (MIMO). MIMO uses more than one sender and receiver antennas and combines this with special coding techniques in order to squeeze even more data through the same frequencies.

Standard	Frequency	Data Rate[1]	Range	Type
802.11a	5 GHz	54 Mbps	120m	LAN
802.11b	2.4 GHz	11 Mbps	140m	LAN
802.11g	2.4 GHz	54 Mbps	140m	LAN
802.11n	2.4/5 GHz	248 Mbps[2]	250m	LAN
802.15.1	2.4 GHz	3 Mbps[3]	100m[4]	PAN
802.15.4	868/915 MHz 2.4 GHz	40 kbps 250 kbps	75m	PAN
802.15.6[5]	1 THz	>1 Gbps	10m	BAN

[1] Specified for outdoor environments with few obstructions.
[2] 802.11n device with two streams (four antennas).
[3] Bluetooth version 2.0.
[4] Bluetooth class 1 device.
[5] All 802.15.6 values are unconfirmed.

Table 2: Comparison of different wireless standards

6 Modulation and signal coding

In order to transmit binary data over the wireless medium it needs to go through a digital to analogue modulation. When the analogue signal is received it needs to be converted back into the digital form so that the binary data is retrieved. The standards uses several different methods to accomplish this seemingly straight forward task. The modulation technique for a standard is usually decided based on the design goals of the standard and the target environment where it will be deployed.

Each technique has different characteristics when it comes to:

- Noise resistance (multi path, fading, etc.)
- Power consumption
- Spectral efficiency (efficient frequency use)
- Hardware complexity

Table 3 lists each standard along with which modulation and coding schemes it can use. Note that not all the schemes are mandatory for each standard. Some of them may be required for interoperability while others are entirely optional depending on which revision of the standard is used. The full name of each of the techniques is listed below the table.

Note that 802.11n is currently only a draft standard and not a fully fledged standard so certain details may change when it is published.

All the different techniques listed in Table 3 has been categorized into the more generic types in Table 4 in order to get a better overview. From Table 4 we can see that all the wireless standards use some kind of PSK scheme, except the new 802.11n which uses QAM and Alamouti STBC.

Technique	802.11a	802.11b	802.11g	802.11n	802.15.1	802.15.4
BPSK	√					√
QPSK	√					
OQPSK						√
DBPSK		√	√			
8DPSK					√	
DQPSK		√	√		√	
$\pi/4$-DQPSK					√	
GFSK					√	
ASK						√
16-QAM	√		√			
64-QAM	√		√	√		
CCK		√				
Alamouti				√		
OFDM	√		√	√		
DSSS		√				√
PSSS						√
AFH					√	

Table 3: Modulation and coding techniques used in the wireless standards

Technique	802.11a	802.11b	802.11g	802.11n	802.15.1	802.15.4
PSK	√	√	√		√	√
FSK					√	
ASK						√
QAM	√		√	√		
CCK		√				
Alamouti				√		
OFDM	√		√	√		
SS		√			√	√

Table 4: Simplified table of modulation and coding techniques

Most of the modulation and coding schemes have long names so they have been abbreviated in Table 3. Below is the full list of names for each of the schemes.

- Phase-Shift Keying (PSK)
  - Binary Phase-Shift Keying (BPSK)
  - Quadrature Phase-Shift Keying (QPSK)
  - Offset Quadrature Phase-Shift Keying (OQPSK)
  - Differential Phase-Shift Keying (DPSK)
    - 8 Phase Differential Phase-Shift Keying (8DPSK)
    - Differential Binary Phase-Shift Keying (DBPSK)
    - Differential Quadrature Phase-Shift Keying (DQPSK)
    - $\pi/4$ Rotated Differential Quadrature Phase-Shift Keying ($\pi/4$-DQPSK)
- Frequency-Shift Keying (FSK)
  - Gaussian Frequency-Shift Keying (GFSK)
- Amplitude-Shift Keying (ASK)
- Quadrature Amplitude Modulation (QAM)
- Complementary Code Keying (CCK)
- Alamouti Space-Time Block Coding (STBC)
- Orthogonal Frequency-Division Multiplexing (OFDM)
- Spread Spectrum (SS)
  - Direct-Sequence Spread Spectrum (DSSS)
  - Parallel-Sequence Spread Spectrum (PSSS)
  - Adaptive Frequency-Hopping Spread Spectrum (AFH)

64-QAM used by 802.11a/g/n manages to map 6 data bits into each transmitted symbol. This is a so called "high order modulation" and it provides a high spectral efficiency when combined with OFDM. The disadvantage of using 64-QAM is that the receiver requires a higher signal to noise ratio (SNR) to demodulate the signal than comparable systems using BPSK and QPSK. This means that in general high order modulations require higher transmit power to achieve the same bit error rate (BER) as a low order modulation like BPSK and QPSK. The use of BPSK and OQPSK (similar to QPSK) in 802.15.4 reflects this fact as the design goal of 802.15.4 was to create devices with low power consumption and so it needs to reduce the power requirements to a minimum.

If the fact that this paper uses about 30 abbreviations to cover most of the differences in the physical layer is any indication that the complexity of wireless standards is high, you might be correct. For a more detailed explanation of the different modulation and coding techniques check out the relevant literature.

References

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