SHORT-RANGE WIRELESS COMMUNICATIONS FOR NEXT-GENERATION NETWORKS: UWB, 60 GHZ MILLIMETER-WAVE WPAN, AND ZIGBEE

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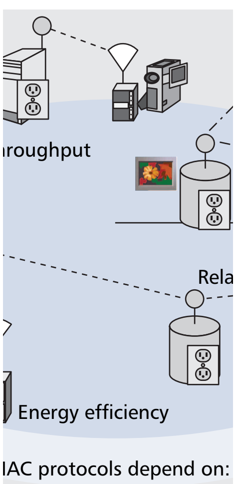

The authors discuss standardization, regulation, and development issues associated with short-range wireless technologies for next-generation personal area networks (PANs).

ABSTRACT

This article presents standardization, regulation, and development issues associated with short-range wireless technologies for next-generation personal area networks (PAN). Ultra-wideband (UWB) and 60 GHz millimeter-wave communication technologies promise unprecedented short-range broadband wireless communication and are the harbingers of multigigabit wireless networks. Despite the huge potential for PAN, standardization and global spectrum regulations challenge the success of UWB. On the other hand, ZigBee™ is expected to be a crucial short-range technology for low throughput and ultra low-power consumption networks. The current status and direction of future development of UWB, emerging 60 GHz millimeter-wave PAN, and low data rate ZigBee are described. This article also addresses wireless MAC protocol issues of 60 GHz multigigabit PAN.

INTRODUCTION

With the rapid evolution of wireless technologies, ubiquitous and always-on wireless systems in homes and enterprises are expected to emerge in the near future. Facilitating these ubiquitous wireless systems is one of the ultimate goals of the fourth-generation (4G) wireless technologies being discussed worldwide today. A wide range of heterogeneous systems, including wireless personal area networks (WPAN), wireless local area networks (WLAN), cellular, WiMAX, and satellite systems will converge into 4G technologies.

As presented in Table 1, the following three technologies are expected to play a vital role in emerging WPAN for broadband or low throughput, low-power consumption applications: ultra-wideband (UWB), 60 GHz millimeter-wave- based WPAN, and ZigBee technologies. UWB technology, proposed for high-speed short-range applications, is one of the more active areas of focus in academia, industry, and regulatory circles. UWB technology affects the basic policy of spectrum regulation by using both the occupied and the unoccupied spectrum across the 3.1–10.6 GHz band. Compared to UWB technology, 60 GHz millimeter wave communications will operate in currently unutilized spectrum and will provide high data rates of up to several gigabits per second for indoor applications. This millimeter-wave environment provides desirable features such as readily available pre-approved radio frequency (RF) spectrum allocation, inherent coexistence with directional antennas, security, and dense deployment. Meanwhile, simple, low data rate WPAN are finding numerous uses in the retail, medical, and logistics fields. In particular, the ZigBee Alliance, an industry consortium promoting a low-power consumption WPAN wireless technology, is developing specifications based on the low rate WPAN of the IEEE 802.15.4-2004 standard. For the WPAN technologies listed in Table 1, selection of Medium Access Control (MAC) protocols is also critical to the performance, cost, and usage. MAC protocols designed to support multigigabit WPAN demonstrate unique features due to applications, data rates, and networking structures.

The physical layer (PHY) specifications and MAC protocols shown in Table 1 are standardized by the IEEE 802.15 WPAN Working Group. Figure 1 shows current standardization activities of the standard body. At the time of this writing, standard processes of 60 GHz millimeter-wave-based WPAN (TG3c) and WPAN low-rate alternative PHY (TG4a) are being developed, and TG3a for UWB was disbanded from the standardization. For current status, see the Web site of the IEEE 802.15 WPAN [1].

In this article, we discuss technologies and issues for deploying next-generation short-range wireless networks, focusing on three technologies: UWB, 60 GHz millimeter-wave-based WPAN, and ZigBee. We present an overview of key technical features, standardization, and regulation, as well as highlighting issues for successful deployment. The wireless MAC protocol of multigigabit 60 GHz WPAN also is addressed.

ULTRA-WIDEBAND WPAN

The first report and order (RAO) of UWB issued by the Federal Communications Commission (FCC) [2] allowed commercialized UWB

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Systems	UWB	60 GHz WPAN	ZigBee
Standard status	Dissolved in IEEE	In progress	Approved
Frequency allocation	3.1–10.6 GHz	57–64 GHz (U.S.) 59–66 GHz (Japan) 57–66 GHz (Europe)[3]	2.4–2.4835 GHz[1] 901–928 MHz[2] 868–868.6 MHz[4]
Channel bandwidth	≥ 500 MHz	Not yet available	2,[1] 0.6,[2] 0.3 MHz[4]
Number of RF channels	2[5] 14[6]	4 (IEEE 802.15.3c)	16,[1] 10,[2] 1[4]
Maximum data rate	100 Mb/s (10 m) 200 Mb/s (4 m) 480 Mb/s (optional)	2 Gb/s (at least) ≥ 3 Gb/s (optional)	250 kb/s[1] 40 kb/s[2] 20 kb/s[4]
Modulation	DSSS,[5] OFDM[6]	Not yet available	BPSK,[2,4] OQPSK[1]
Maximum coverage	~10 m	~20 m	~20 m
Channel access	Hybrid multiple access (Random and guaranteed access)		CSMA/CA (Optional) guaranteed time slot

[1] 2.4 GHz band ZigBee
[2] 915 MHz bands ZigBee
[3] This frequency band is under consideration.
[4] 868 MHz band ZigBee
[5] DS-UWB
[6] MB-OFDM

Table 1. *Summary of characteristics of UWB, 60 GHZ millimeter-wave-based WPAN, and ZigBee.*

The United States, Europe, and Asia are struggling to define a unified spectrum regulation and standard. Globally, this short-range, high-throughput WPAN technology with data rates of several hundred megabits per second creates opportunities and challenges.

devices in the United States and provided momentum to the worldwide regulation and standardization of UWB. The United States, Europe, and Asia are struggling to define a unified spectrum regulation and standard. Globally, this short-range, high-throughput WPAN technology with data rates of several hundred megabits per second creates opportunities and challenges. In this section, we present an overview of UWB technologies, issues, and status of standardization and regulation.

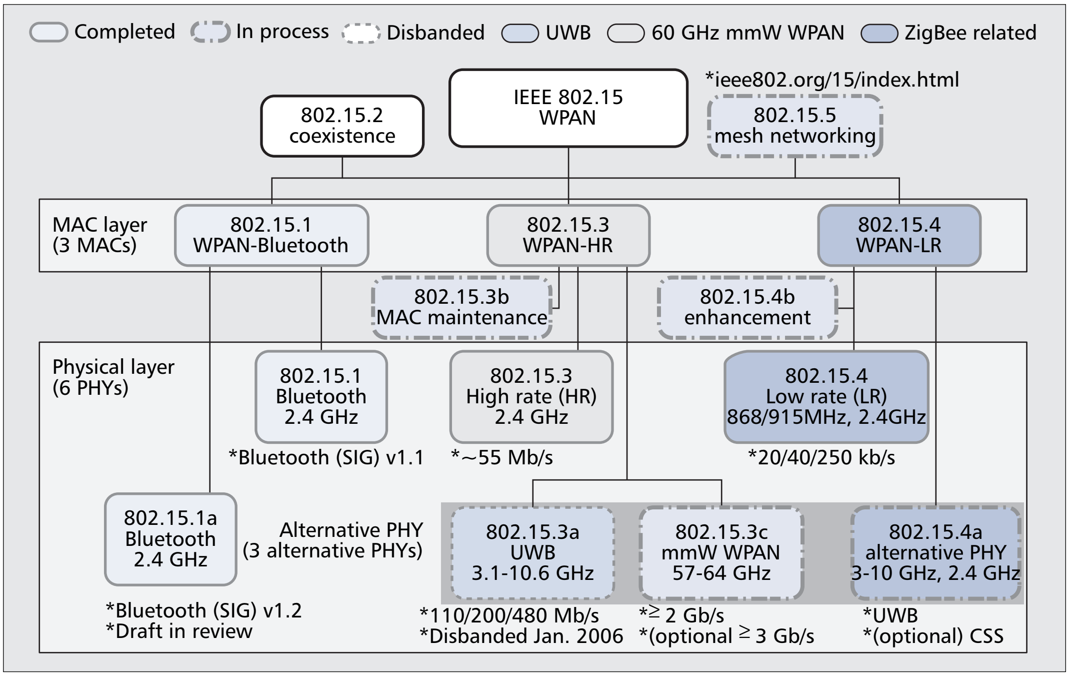
UWB Technologies

UWB technologies using short-pulse signals have been applied to radar systems since the 1960s, and their communication applications have attracted industry and academia since the 1990s. In addition to communication applications, the UWB devices can be used for imaging, measurement, and vehicular radar. According to the requirement of the first RAO of the FCC, the fractional bandwidth or the transmission bandwidth of UWB signals should be greater than 0.2 or 500 MHz, respectively; this open definition does not specify any air interface or modulation for UWB. In the early stages, time-domain impulse radio (IR) dominated UWB technologies and still plays a crucial role. However, driven by the first RAO and standardization activities, conventional modulation schemes, such as multiband orthogonal frequency domain multiplexing (MB-OFDM) have appeared. Figure 2 shows fundamental PHY features of two UWB proposals, direct sequence (DS)-UWB and multiband MB-OFDM.

Direct Sequence (DS)-UWB — The DS-UWB adopts variable-length spreading codes for binary phase shift keying (BPSK) or (optional) quadrature bi-orthogonal keying (4BOK) modulations [3]. A data symbol of BPSK (one bit) and 4BOK (two bits) modulation is mapped into a spreading sequence and bi-orthogonal code with length ranging between 1 and 24, respectively. It can provide (optionally) a maximum data rate of 1.32 Gb/s. Chip rate can be changed from 1313 to 2730 Mchips/s according to data rates and piconet channels. There is a difference between each chip rate of piconet channels of about 13 MHz, and carrier frequency is exactly a multiple of three times the chip rate. As a receiver structure, the Rake receiver is generally assumed to mitigate an adverse effect of multi-path. DS-UWB supports two spectrum bands of operation, the lower band (3.1–4.85 GHz) and the optional upper band (6.2–9.7 GHz). Each operation band has six piconet channels, where distinguished spreading codes, chip rates, and center frequencies are specified.

For DS-UWB, efficient synchronization and detection are critical to realize the technology. Although Rake reception is generally assumed to capture the spread energy over multi-path

The failure of unified standardization will cause confusion in the market and impair the potential of UWB. The MB-OFDM proposal of the WiMedia Alliance is receiving wide support from many companies and consortiums.



■ **Figure 1.** *IEEE 802.15 Working Group for WPANs.*

propagation, the complexity of the ideal Rake receiver creates a realization problem. In addition, long acquisition times must be addressed. Regarding piconets, there is a question as to whether the given spreading gains and structures are sufficient for coexistence of piconets.

Multiband OFDM — Finding a realistic solution to avoid pulse-related issues of impulse radio (IR) UWB drives the MB-OFDM scheme that combines OFDM modulation and multiband transmission [4]. The MB-OFDM uses a 128-point inverse fast Fourier transform (IFFT) and FFT with a subcarrier spacing of 4.125 MHz (528 MHz /128). Each data subcarrier is modulated by a quadrature phase-shift keying (QPSK) symbol. Zero-padded suffix of length 32 samples (60.61 ns) and a guard interval of five samples (9.47 ns) are used to prevent multi-path or inter-block interference and guarantee band switching time, respectively. Modulation can use time- and frequency-domain spreading of an order of two by repeating identical data in time- or frequency domain, respectively. Maximum data rate of 480 Mb/s can be provided. The multiband mechanism of MB-OFDM provides five band groups over 3.1–10.6 GHz and each band group consists of three different bands except the last group that is composed of two bands. In addition, a time-frequency code (TFC), that specifies a sequence of frequency bands for OFDM symbol transmission, is used to interleave information data over a band group.

Although this proposal avoids the disadvantages of IR schemes, the inherently high peak-to-average power ratio (PAPR) of the OFDM and the sensitivity to frequency offset, timing error, and phase noise creates challenges for circuit design and a power-efficient implementation. For example, in an extreme case, the PAPR of the MB-OFDM can be approximately 20 dB, and this large PAPR may restrict the achievable power efficiency and power amplifier design.

UWB Regulation and Standardization

After the Notice of Inquiry (1998) and Notice of Proposed Rule Making (2000), the FCC issued the first RAO related to UWB in February 2002 [2]. The RAO approved unlicensed spectrum use in the 3.1–10.6 GHz band for communication and imaging devices with the power spectrum density (PSD) limited to –41.3 dBm/MHz or 75 nW/MHz to restrict the interference from UWB to other services. The second RAO, which became effective in March 2005, reaffirmed the first RAO and modified test methods for UWB devices. In Europe, the Electronic Communications Committee (ECC) TG3 of the European Conference of Postal and Telecommunications Administrations (CEPT) published ECC Report 64 for UWB in February 2005, wherein it asserted that Europe should prepare its own spectrum mask. In addition, the European Telecommunications Standards Institute (ETSI) proposed its own UWB spectrum mask with more stringent PSD limits than the FCC mask at both band edges [5]. European spectrum regulation was scheduled to be defined in 2006. In Japan, the Ministry of Internal Affairs and Communications (MIC) has approved a preliminary emission policy over the 3.4–4.8 GHz and 7.25–10.25 GHz bands, where the emission limits are similar to the FCC rule. Over the 3.4–4.8 GHz band, a detection and avoidance (DAA) mechanism is required for the emission level of –41.3 dBm/MHz; otherwise, –70 dBm/MHz is required. In Korea, the Ministry of Information and Communication (MIC) plans to allow test spectrum for UWB over the 3.1–5 GHz band. Above all, Korea wants to protect the WiBro, satellite digital multimedia broadcasting (DMB), and 3G cellular services from UWB-related interference. With the expected global introduction of UWB technologies, Task Group

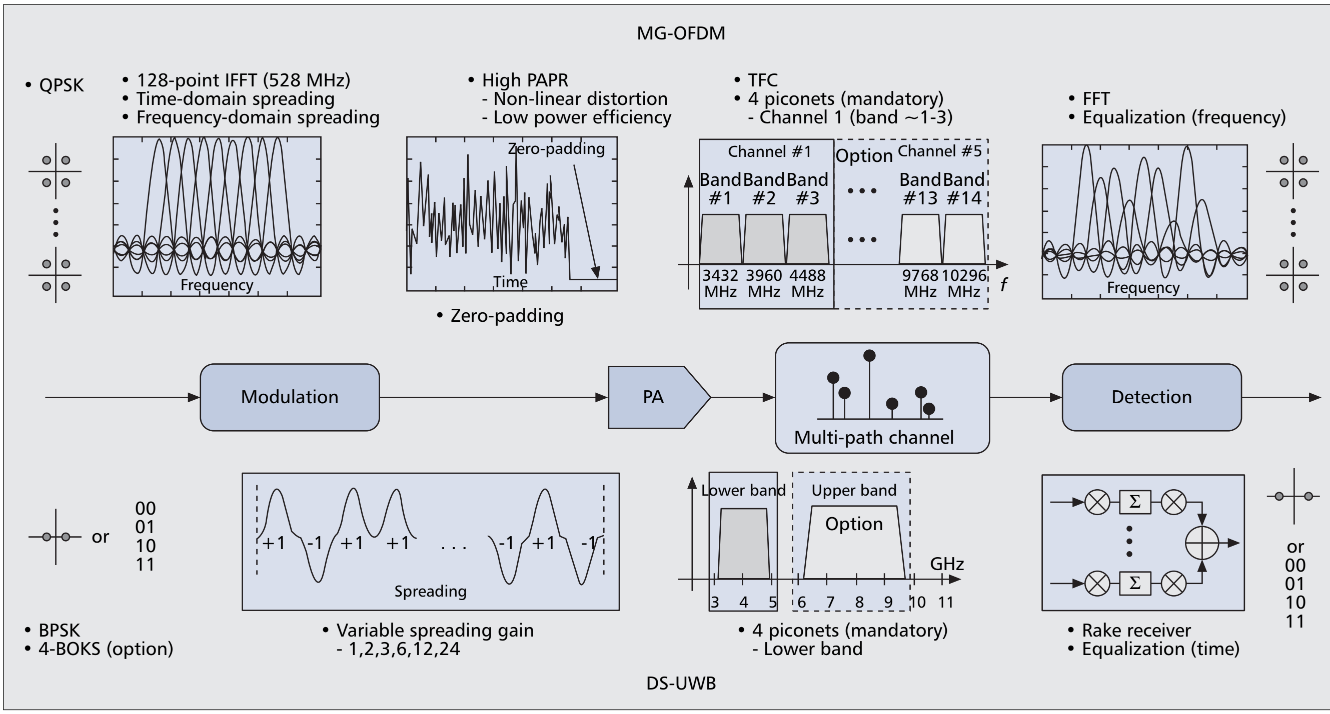


Figure 2. *UWB technologies; DS-UWB and MB-OFDM [1].*

1/8 under Study Group (SG) 1 of ITU-R formed in July 2002 is preparing recommendations for UWB regulations.

The standard process of the IEEE 802.15 TG3a, defining an alternative PHY specification compatible with the MAC standard of IEEE 802.15.3-2003, was dissolved in January 2006 due to the heated competition and resulted deadlock between two proposals, DS-UWB and MB-OFDM. The failure of unified standardization will cause confusion in the market and impair the potential of UWB. The MB-OFDM proposal of the WiMedia Alliance is receiving wide support from many companies and consortiums, such as the Wireless USB Promoter Group (2004) and the Wireless 1394 Trade Association (2004). In addition, Ecma International approved two standards for UWB, based on MB-OFDM technology in December 2005. On the other hand, DS-UWB is about one year ahead of the MB-OFDM camp in silicon devices and products with optional higher data rates. Although the UWB Forum of DS-UWB suggested a common signaling mode (CSM) and a dual-PHY standard as a compromise in the failed standardization process, the Multiband OFDM Alliance (MBOA, now merged with WiMedia Alliance) responded negatively. Besides the IEEE 802.15 TG3a, there are several projects related to UWB standardization all over the world, such as the pervasive ultra-wideband low-spectral energy radio systems (PULSERS) within the 6th Framework Programs (FP6) of the European Information Society Technologies (IST). As of July 2007, Dell Computers and Lenovo announced pending shipments of MB-OFDM UWB technology in some laptops using Wiquest silicon, and UWB chip makers such as Alereon and Intel expect to be shipping MB-OFDM in the next several weeks.

60 GHz Millimeter-Wave-Based WPAN

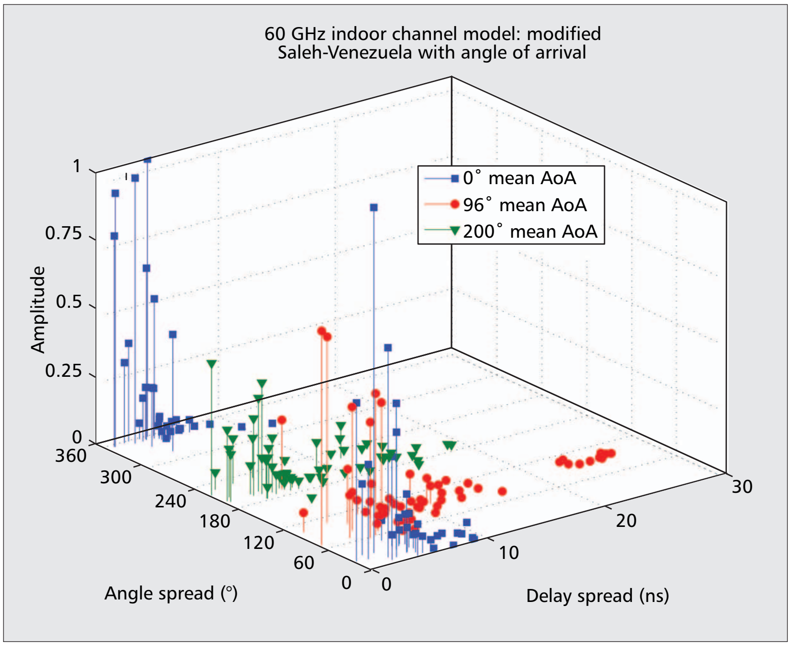
The 60 GHz millimeter-wave radio can provide medium- and short-range wireless communications with a variety of advantages. Huge and readily available spectrum allocation, dense deployment or high frequency reuse, and small form factor can pave the way to multigigabit wireless networks [6]. This section begins by describing some distinguished features that make the millimeter-wave band attractive for broadband short-range wireless systems. An overview of standardization, regulation, and related issues also is provided.

Why 60 GHz?

Throughout the world approximately 5–7 GHz bandwidth is available over the 60 GHz millimeter-wave band. This continuous and clean bandwidth facilitates multigigabit wireless transmission. Moreover, this readily available, pre-approved spectrum allocation obviates regulation conflicts. When considering the regulatory delay of UWB, this prospect is very encouraging.

In addition to clear and large spectrum allocation, the 60 GHz millimeter-wave channel shows higher path loss than the lower microwave bands. In addition, the atmospheric oxygen (O_2) absorption and rain interference are known to increase attenuation by 10–15 dB/km beyond 2 km. The propagation properties of indoor 60 GHz channel decrease interference to other systems or collocated 60 GHz networks and increase frequency reuse factors and space efficiency [7]. Furthermore, high signal attenuation can strictly confine the physical range of a network, which enables more secure wireless communications.

The size of a product, as well as technical performance, can become a crucial factor for



■ **Figure 3.** *60 GHz indoor channel model by using a modified Saleh-Venezuela model with angle of arrival (AoA): cluster arrival rate $\lambda = 1/2.833$ ns, cluster decay factor $\Gamma = 9.09$ ns, ray arrival rate $\lambda = 1/0.642$ ns, ray decay factor $\gamma = 1.25$ ns, and standard deviation of AoA $\sigma = 10.47°$ with three mean angle arrivals, 0°, 96°, and 200°. Channel parameters are based on the measured data from IEEE 802.15 Working Group TG3c.*

marketing. An antenna or other RF components of 60 GHz frequency can be implemented in a slimmer size than other microwave band systems due to a short wavelength of about 5 mm. Thus, we can shrink mobile or portable wireless devices of 60 GHz millimeter-wave-based WPAN.

Millimeter-Wave-Based WPAN Regulation and Standardization

The United States and Japan have issued spectrum regulations about the millimeter-wave band, and Europe is preparing its regulation. In August 2000, Japan issued a regulation for 60 GHz millimeter-wave for high-speed data communication, and in the regulation, both the licensed (54.25–59 GHz) and the unlicensed band (59–66 GHz) were specified. For the license-exempted band, maximum output power is limited below 10 mW, and the maximum channel bandwidth is restricted as 2.5 GHz. Regarding the licensed band, 100 mW output power with 20 dBi antenna gain is allowed. The FCC assigned 57–64 GHz frequency band as an unlicensed band by FCC 47 CFR 15.255. In short, the rules are similar to other regulations for unlicensed bands and mainly consider WLAN applications. Power density measured at 3 m is restricted to an 18 $\mu W/cm^2$ in peak with average density of 9 $\mu W/cm^2$. The maximum peak power is limited to 500 mW. In Europe, standards are being developed for 57–66 GHz band by CEPT (ECC) and ETSI. At present, maximum transmit power of 57 dBm effective isotropic radiated power (EIRP) with a minimum spectrum requirement of 500 MHz is proposed.

After the FCC gave authorization for 57–64 GHz use without a license, standardization for short-range broadband wireless communications over the band was accelerated by the IEEE 802.15 Task Group TG3c and was officially approved in March 2005. TG3c is developing a millimeter-wave-based alternative PHY for the existing high-rate WPAN standard IEEE 802.15.3-2003. The proposals for physical layer specification were scheduled to be presented in November 2006, and standardization activities are expected to be finished by 2007. According to the system requirement, this standard will provide a data rate of at least 2 Gb/s, and optionally in excess of 3 Gb/s. For current status, see [1]. In Japan, after undertaking several research projects during the 1990s, the association of radio industries and businesses (ARIB) defined a fixed wireless access (FWA) standard, STD-T74, for video distribution and gigabit wireless link in May 2001. Recently Japan has launched the Millimeter-Wave Personal Area Communication Systems (MPACS) expert group in the Asia Pacific Telecommunity (APT). In Europe, the MEDIAN project (1994–1997) investigated a short-range WLAN (4–6 m) that could provide a maximum data rate of 150 Mb/s, using OFDM modulation. After MEDIAN, the BroadWay project is developing a dual frequency hybrid WLAN bridging the 5 GHz and 59–64 GHz bands. It can provide (optionally) a maximum data rate of 720 Mb/s at short range, using a 64-QAM OFDM modulation. In addition, the MAGNET and WINNER projects of IST are focusing on short-range WPAN. In addition to these ETSI projects, the WIGWAM project, funded by Germany, also is developing a short-range communication system with a data rate of 1 Gb/s, using OFDM modulation.

Issues for 60 GHz Millimeter-Wave-Based WPAN

The 60 GHz millimeter-wave band evidently provides short-range wireless systems with unprecedented advantages in terms of bandwidth, high space efficiency, security, and form factor. However, this millimeter-wave spectrum also poses challenges that must be resolved for successful deployment as described in the following.

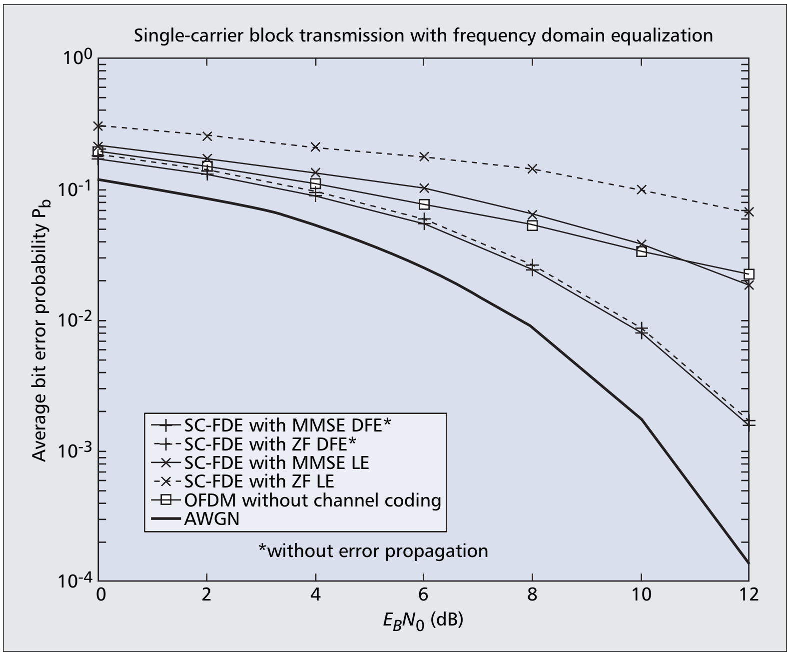
Channel Analysis and Modeling — Measured data of indoor broadband 60 GHz channels show high dependence on the surrounding environments. According to the measurements being analyzed in the TG3c, path loss exponent and RMS delay spread are approximately 1.2–4.4 and 0.25–45 ns, respectively [7, 8]. The angle of arrival (AoA) distribution standard deviation modeled as a Laplacian distribution is about 14°. Thus, it is desirable to specify channel parameters, including path loss exponent, delay spread, and angle spread, in connection with specific application scenarios or usage models. The channel subcommittee of TG3c classifies channel environments according to surrounding (e.g., residential or office) and propagation line-of-sight or non-line-of-sight (LOS or NLOS) environments. One of the difficulties in analyzing measured data is that measurements are coupled with specific antennas and settings. For general channel modeling, how to decouple or couple these specific settings is a difficult task.

Regarding multiple antenna systems, multiple-input multiple-output (MIMO) channel measurements are very rare and correlation and rank of 60 GHz MIMO channel[s] have not been analyzed sufficiently yet. In the literature, there is still confusion whether an indoor 60 GHz channel can allow spatial multiplexing (SM) of general MIMO systems.

When considering documents of TG3c, tapped delay line or modified Saleh-Venezuela (S-V) models can be applied for 60 GHz indoor channel modeling [7]. The tapped delay line model has channel taps (or coefficients) of specific relative power with Rayleigh or Rician small-scale variations. The modified S-V model adds AoA information to a conventional model. S-V channel modeling, which has been widely used for indoor, narrow band channel modeling, describes multi-path propagation as a combination of clusters and rays per each cluster with Poisson arrival rates. Figure 3 shows simulation result of 60 GHz indoor channel based on the modified S-V model with AoA and measurement parameters of [7, 8].

Modulations — Modulation issues of 60 GHz millimeter-wave WPAN can create similar circumstances or controversies for UWB between DS-UWB and MB-OFDM. As described in the previous section about standardization, several European projects have proposed OFDM-based systems, and Japan's project has designed a single-carrier system using amplitude-shift keying (ASK) modulation. Directional or array gains that can be combined with modulations though spatial multiplexing of multiple antennas seem to require more consideration.

OFDM modulation of 60 GHz WPAN must address high PAPR and sensitivity of phase and carrier offset. High PAPR causes nonlinear distortion and low-power efficiency in the power amplifier. Due to the high carrier frequency, phase noise and carrier offset will degrade the performance of OFDM. General single carrier modulations over 60 GHz multipath channels are unfeasible due to the required high complexity of equalization. However, block transmission using single-carrier modulation with frequency domain equalization (SC-FDE) can achieve complexity and performance comparable with OFDM modulation without high PAPR and phase noise sensitivity [9]. Block transmission of SC-FDE appends cyclic prefix at the transmitter to prevent interblock interference and uses FFT, frequency domain equalization, and IFFT at the receiver. Data detection is performed in the time domain after IFFT operation. Performance of SC-FDE using frequency-domain equalizations under 60 GHz indoor channel environment are presented in Fig. 4.



■ **Figure 4.** *Performance of single-carrier block transmission with frequency domain equalization over 60 GHz indoor channel: 16-QAM modulation with 256 data symbols and 64 cyclic prefix per block. Channel model of a 60 GHz indoor (office) environment based on measured data from France Telecom R&D, Table 11, which is available at http://www.ieee802.org/15/pub/TG3ccontributions.html, is used.*

Broadband Circuit Technologies — Conventionally, 60 GHz RF circuits have been realized using III-V compound technologies such as gallium arsenide (GaAs) and indium phosphide (InP). GaAs-based monolithic microwave integrated circuits (MMIC) are available in the market today. However, the price of the solution is still too expensive to be adopted in WLAN or consumer applications, and mass production also is difficult. While complementary metal oxide semiconductor (CMOS) technology is considered as an ideal solution in the point of cost and circuit integration, RF CMOS for 60 GHz frequency requires more performance improvement. Considering performance and cost, currently, silicon germanium (SiGe) technology seems to be a promising alternative to the GaAs or InP technology. The SiGe solution provides MMIC circuits with a tolerable noise figure and power dissipation. Besides circuit technologies, 60 GHz circuits make possible or require new implementation methodologies. For example, antenna-on-chip design or implementing antennas by using wire bonding shrinks the size of the system. Analogue processing for equalization and synchronization may deal with speed and power consumption issues.

ZigBee Technology

Although wireless control and sensor networking are at the other end of high-speed networks with quality of service (QoS) support, these low-power consumption and low-data rate WPAN are driven by applications in the retail, medical, and logistics fields. This low throughput and low-cost wireless technology, named ZigBee, adopts the IEEE 802.15 TG4 low-data rate WPAN standard. Its specification, which was defined by the ZigBee Alliance, specifies network, security, and application profiles based on PHY and MAC sublayers of IEEE 802.15.4-2003 standard [10, 11].

IEEE 802.15.4-2003 Standard and ZigBee

The IEEE 802.15.4-2003 PHY operates in three different industrial, scientific, and medical (ISM) bands; 2450, 915, and 868 MHz. The 2450 MHz (global) band provides 16 channels; the 915 MHz (United States) and 868 MHz (Europe)

While low throughput and low-power consumption networking hold great potential, several open issues must be addressed for a successful realization of the potential. The crucial issue is how to realize a low-power consumption and low-cost network of ZigBee devices.

bands are assigned 10 channels and a single channel, respectively. For the three ISM bands, two PHY options, 2450 MHz and 915/868 MHz PHY, are specified that support data rates of 250 kb/s and 40/20 kb/s, respectively. 2450 MHz PHY maps a data symbol composed of four information bits into one of 16 quasi-orthogonal 32-chip PN sequences and modulates it using offset quadrature phase shift keying (OQPSK). On the other hand, 915/868 MHz PHY maps a binary data symbol into one of two 15-chip PN sequences and transmits the chip sequence using BPSK. The basic channel access mechanism of TG4 is a carrier sense multiple-access with collision avoidance (CSMA-CA) and is suitable for very low-duty cycle operation. For applications requiring specific data bandwidth, one of two optional superframe structures provides a guaranteed time slot (GTS) for low latency. A device implementing the IEEE 802.15.4-2003 protocol can be classified as a full function device (FFD) or reduced function device (RFD). In brief, both the PHY specification and the MAC protocol achieve the required long battery life and simplicity by using spread spectrum transmission and very low duty cycle.

In addition to the standard IEEE 802.15.4-2003, low rate alternative PHY task group, TG4a is defining an enhanced PHY specification over TG4 in throughput, power consumption, and range. The approved draft specification of TG4a considers two PHY, that is, IR-based UWB for both communication and ranging over 3–10 GHz band and (optionally) narrowband chirp spread spectrum (CSS) for communication only over 2450 MHz. IR-based UWB adopts a combination of pulse position modulation and BPSK and provides data rate of 842 kb/s with several optional rates. CSS spreads differential QPSK of quasi orthogonal PN sequences by using chirp spread spectrum and supports data rates of 1 Mb/s or optional 250 kb/s.

The ZigBee specification, defined by an association of companies called the ZigBee Alliance, provides upper layer stacks and application profiles that are compatible with the IEEE 802.15 TG4 PHY and MAC sublayers. Similar to RFD and FFD, the specification also describes nodes as network coordinators, routers, and end devices. Network coordinators manage the network, and routers direct messages between nodes. Data traffic of ZigBee networking can be classified as three different types: periodic, intermittent, and repetitive low-latency data. According to these traffic types, optimized network configuration can be chosen. Generally, ZigBee networks are suitable for low duty cycle (≈ 1 percent) communications for long battery life. Besides the technical specifications, the ZigBee Alliance also manages product branding of ZigBee-compliant platforms. Recently Freescale and several other companies announced platforms including chip sets, development environment, and protocol stacks.

Issues and Challenges

While low throughput and low-power consumption networking hold great potential, several open issues must be addressed for a successful realization of the potential. The crucial issue is how to realize a low-power consumption and low-cost network of ZigBee devices. This challenging task cannot be accomplished by an isolated methodology alone; a system-level approach ranging over wide layers is required.

Networking and Application Profiles — Frequently changing network environments caused by node movement and failure require networking and upper layers to offer very robust and self-configurable mechanisms. These mechanisms and applications should select an appropriate networking topology because power consumption depends on networking structure and device type. A robust routing algorithm also is an issue for multihopping or mesh ZigBee networks. Furthermore, due to limited resources, including memory, power, and computational capacity, network stacks must be realized in an efficient and compact form; for example, the ZigBee Alliance suggests an eight-bit microprocessor and either 32 kilobytes (FFD) or six kilobytes (RFD) memory.

Device Implementation — For ZigBee device realization, a highly integrated single chip using CMOS technology is preferred to combine analog and digital circuits with tolerable RF performance. The choice of transceiver architecture is a trade-off among cost, complexity, performance, and power consumption. Zero-IF or direct conversion is one of the promising candidates because it enables digital preferred design, low power, and simplicity. In addition to hardware design, software implementation also must consider characteristics of ZigBee devices. For example, the protocol stack, operating system (OS), and compiler must operate with limited memory and computing capacity.

Multi-month to Multi-year Battery Life — The goal of multi-month to multi-year battery life creates challenging tasks for ZigBee designers in circuit design, battery technology, PHY specification, and protocol stacks. Most of ZigBee applications are expected to operate with a very low-duty cycle, thus power consumption in sleep or power-down mode can significantly affect battery life. Avoiding leakage current also requires careful circuit design. Most of the currently available ZigBee devices consume several orders of microamps in power-down mode. Reception and wake-up operations of an RF circuit require a considerable portion of total energy consumption. Using current technology, approximately 20–50 mA is consumed for RF circuit operation in a ZigBee transceiver. In addition to circuit implementation, applications and network profiles must also support low-power operations.

MAC Protocols for Multigigabit WPAN

A wireless MAC protocol is a rule by which nodes of a network can share a common spectrum in an efficient and fair manner. A MAC protocol of a short-range ad hoc network targeted by a multigigabit WPAN, especially 60 GHz millimeter-wave WPAN, requires a distinctive

MAC protocol differentiated from the general ad hoc MAC protocols surveyed in [12]. The IEEE 802.15 TG3c decided to define a new MAC protocol compatible with 60 GHz millimeter-wave WPAN. Channel and networking characteristics of multigigabit WPAN, as well as assumed applications, should be reflected in the MAC protocol. Figure 5 shows the main issues of 60 GHz multigigabit WPAN: directional antennas, high throughput, relay channels, streaming, energy efficiency, and interference and co-existence. In this section, high throughput, directional antennas, and implementation issues of millimeter-wave-based WPAN MAC protocol are addressed.

High Throughput

A wireless data bus and uncompressed HDTV video streaming, which are potential applications of multigigabit WPAN, require unprecedented high throughput; for an 1080i HDMI connection, data rate of 2 Gb/s is assumed at the application level. This high throughput of 60 GHz WPAN requires not only a multigigabit physical layer but an efficient MAC protocol as well.

Bandwidth waste caused by frame and packet structures restricts achievable throughput. In the high speed physical layer compatible with multigigabit transmission, overheads existing in conventional preamble and header fields of packet or frame aggravate the throughput more severely than narrow-band transmission. Thus, for example, a superimposed training sequence embedded in the information data can be adopted by 60 GHz WPAN to reduce the overhead. Maximum frame and packet sizes also are factors to investigate for throughput improvement. Throughput is greatly influenced by signaling and control mechanisms, as well as frame structures. In particular, retransmission caused by collisions or errors substantially consumes the data bandwidth. To minimize retransmission, 60 GHz MAC protocol may realize a hybrid automatic repeat request (ARQ) that combines ARQ and error correction coding. In addition, retransmission and ARQ can refer to channel state information (CSI), such as signal-to-noise ratio (SNR) for adaptive control operations. In addition to parameter and control optimization, an efficient channel access scheme also is crucial to throughput improvement. Reserved-based channel access, generally adopted to provide guaranteed bandwidth in WPAN, may require modification under given 60 GHz WPAN networking and application scenarios.

Directional Protocols

Severe attenuation of 60 GHz radio propagation and the resulting low-link budget make high gain or directional antennas feasible for 60 GHz WPAN. There is an ongoing discussion to consider directional MAC protocols at the IEEE 802.15 TG3c although omni-directional antennas are assumed for standardized WPAN and WLAN. In particular, 60 GHz WPAN can obtain the benefit of directional antennas using multiple antennas due to small wavelength (≈ 5 mm). Directional antennas have the potential of higher spatial reuse, longer coverage, less interference, and higher energy efficiency than omni-directional antennas, as surveyed in [13].

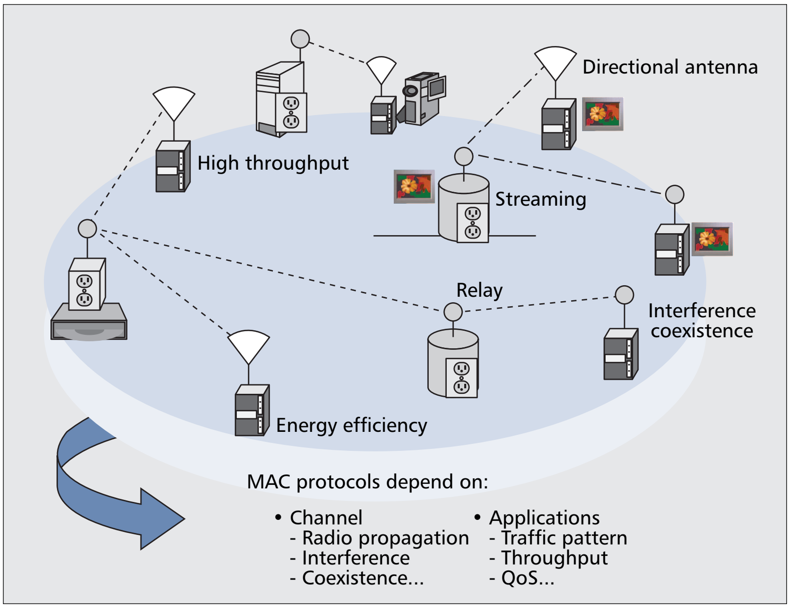


Figure 5. *MAC protocol issues of 60 GHz WPANs: high throughput, directional antennas, relay channels, video streaming, and interference and coexistence.*

However, directional antennas and MAC protocols, especially in the short-range ad hoc networks, require cautious consideration in terms of the trade-off between complexity and performance. Although most proposed directional protocols deal with switched-beam antennas due to simplicity, fully adaptive arrays or general MIMO antennas deserve to be studied further. In technical aspects, estimating directions or positions is a challenging task under limited computing capacity and ad hoc networking environments. Special signaling or procedure for estimations should be provided. Because the beam width of a 60 GHz radio propagation is narrower compared with microwave radio, misaligned directional antennas may lead to degradation and aggravation of received SNR and interference level, respectively. Regarding channel access, most of the proposed directional protocols are based on the request-to-send/clear-to-send (RTS/CTS) and network allocation vector (NAV) of the IEEE 802.11 distributed coordination function (DCF) mechanism [12]. However, 60 GHz WPAN may require reservation-based directional protocols due to QoS support and applications. In addition, there are directional antenna-inherent issues, such as new hidden node problems and deafness caused by mainly asymmetric gains of directional antennas. For the assumed frequently changing ad hoc networking, these node problems should be addressed efficiently.

Implementation and Simulation Platforms

When considering practical aspects of MAC protocol implementation, there are a variety of trade-offs among architectural requirements, performance requirements, and complexity. Optimal partition between hardware and software based on these factors is crucial to a successful realization of the MAC protocol. Growing trends toward system-on-a-chip (SoC)

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design combine a processor (e.g., ARM™) with dedicated custom hardware for MAC operations. Generally, special frame handling such as acknowledgment or control handshaking is processed by hardware for fast response. The timer, a cyclic redundancy check (CRC), and encryption/decryption are also hardware functions. On the other hand, network management and control operations are implemented in software. Regarding partition issues, the interface is an interesting topic because wireless MAC has links with radio, baseband, state registers, and host parts. In addition, partition, buffering, and direct memory access (DMA) operations require careful attention to support high throughput of multigigabit wireless MAC.

Along with implementation issues, several simulation platforms are discussed in the documentation of an IST project related to WPAN [14]. Although performance depends on specific requirements and environments, OpNet™ and Network Simulator 2 (NS-2) seem to be widely accepted for network protocol designs to date. OMNeT++, Ptolemy II, GloMoSim, and recently, SystemC also show strength in particular areas. These platforms, however, seem to require more WPAN protocols and wireless channel environments. In addition to these simulation platforms, site-specific tools such as LANPlanner™, which visualizes coverage, capacity, and physical location for WLAN design and deployment, also are available.

Conclusions

This article describes potential technology for the next-generation WPAN, namely UWB, 60 GHz millimeter-wave-based WPAN, and ZigBee and gives an overview of related standardization and regulation issues. We highlighted UWB and 60 GHz millimeter-wave-based WPAN and ZigBee as harbingers of next generation WPAN for multigigabit and low-rate networks, respectively. UWB technology has a huge potential for short-range, broadband wireless communications and is under worldwide development. We emphasized that the standardization breakdown of IEEE 802.15 TG3a and different views regarding spectrum regulations are threatening global deployment of UWB. We described key features of two UWB technologies, DS-UWB and MB-OFDM, and discussed global status of standardization and regulation. In addition to UWB technology, 60 GHz millimeter-wave-based short-range wireless communications are expected to play a crucial role for multigigabit WPAN in the near future. We highlighted the characteristics and development status of 60 GHz short-range communications. To realize multigigabit 60 GHz communications, accurate channel modeling, efficient modulations, and broadband circuits must be addressed. In addition to high data rate WPAN, we also discussed a low data rate, low cost, and ultra low-power consumption technology named ZigBee. Although it is on the other end of UWB and 60 GHz millimeter-wave WPAN in data rate, ZigBee has potential in sensor networks and the wireless inventory tracking control of next generation wireless networks.

Together with PHY technology, upper layer protocols also are crucial for next-generation broadband WPAN. We focused on the MAC sublayer of multigigabit WPAN and described the issues of high throughput and directional antennas. Additionally, we highlighted an optimized partition of MAC functions between hardware and software.

In conclusion, UWB, 60 GHz WPAN, and ZigBee are potential technologies to realize short-range wireless communications of 4G technology. To successfully deploy these WPAN in the near future, globally unified standardization and regulations, as well as technical issues should be addressed.

References

[1] IEEE 802.15 WG for WPAN Web site; available at http://grouper.ieee.org/groups/802/15/

[2] FCC, "First Report and Order: Revision of Part 15 of the Commissions Rules Regarding Ultra-Wideband Transmission Systems," ET Docket 98-153, Apr. 2002.

[3] R. Fisher *et al.*, "DS-UWB Physical Layer Submission to 802.15 Task Group 3a," IEEE 802.15 3G doc., IEEE 802.15- 04/137r3, July 2004.

[4] A. Batra *et al.*, "Multiband OFDM Physical Layer Proposal for IEEE 802.15 Task Group 3a," MBOA-SIG, Sept. 2004.

[5] D. Porcino, "Standardization and Regulations for UWB," ULTRAWAVES IST-2001-35189, D9.4, Jan. 2005.

[6] P. Smulders, "60 GHz Radio: Prospects and Future Directions," *Proc. 10th IEEE Symp. Commun. and Vehic. Tech.*, Benelux, Nov. 2003, pp. 1–8.

[7] IEEE 802.15.3, "Channel Model Literature Summary and Capacity Calculations"; http://www.ieee802.org/15/pub/TG3c contributions.html

[8] H. Hao, V. Kukshya, and T. S. Rappaport, "Spatial Characteristics of 60-GHz Indoor Channels," *IEEE JSAC*, vol. 20, no. 3, Apr. 2002, pp. 620–30.

[9] M. Huemer *et al.*, "A Review of Cyclically Extended Single Carrier Transmission with Frequency Domain Equalization for Broadband Wireless Transmission," *Euro. Trans. Commun.*, vol. 14, no. 4, Jul.–Aug. 2003, pp. 329–41.

[10] ZigBee Alliance, "ZigBee Specification," doc. 053474r06, v. 1.0, Dec. 2004.

[11] IEEE Std. 802.15.4, "Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)," Oct. 2003.

[12] S. Kumar, V. S. Raghavan, and J. Deng, "Medium Access Control Protocols for Ad Hoc Wireless Networks: A Survey," *Elsevier Ad Hoc Networks*, vol. 4, no. 3, May 2006, pp. 326–58.

[13] A. Arora and M. Krunz, "Power-Controlled Medium Access for Ad Hoc Networks with Directional Antennas," *Elsevier Ad Hoc Networks*, 2006.

[14] IST PULSERS, "Definition of New Concepts/Architecture for UWB MAC and Networking," tech. rep. D51.1a, July 2004.

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