Ultra-Wideband Radio Technology: Potential and Challenges Ahead

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ABSTRACT

An unprecedented transformation in the design, deployment, and application of short-range wireless devices and services is in progress today. This trend is in line with the imminent transition from third- to fourth-generation radio systems, where heterogeneous environments are expected to prevail eventually. A key driver in this transition is the steep growth in both demand and deployment of WLANs/WPANs based on the wireless standards within the IEEE 802 suite. Today, these short-range devices and networks operate mainly standalone in indoor home and office environments or large enclosed public areas, while their integration into the wireless wide-area infrastructure is still nearly nonexistent and far from trivial. This status quo in the short-range wireless application space is about to be disrupted by novel devices and systems based on the emerging UWB radio technology with the potential to provide solutions for many of today's problems in the areas of spectrum management and radio system engineering. The approach employed by UWB radio devices is based on sharing already occupied spectrum resources by means of the overlay principle, rather than looking for still available but possibly unsuitable new bands. This novel radio technology has recently received legal adoption by the regulatory authorities in the United States, and efforts to achieve this status in Europe and Asia are underway. This article discusses both the application potential and technical challenges presented by UWB radio as an unconventional but promising new wireless technology.

INTRODUCTION

When designing future short-range wireless systems one needs to take into account the increasingly pervasive nature of communications and computing based on the vision that wireless systems beyond the third generation (3G) will enable connectivity for "everybody and everything at any place and any time." This ambitious view assumes that the new *wireless world* will be the result of a comprehensive integration of existing and future wireless systems, including wide area networks (WANs), wireless local area networks (WLANs), wireless personal area and body area networks (WPANs and WBANs), as well as ad hoc and home area networks that link devices as diverse as portable and fixed appliances, personal computers, and entertainment equipment. However, the realization of this vision requires the creation of new wireless technologies and system concepts offering easy-to-use interfaces with the user at the center, as in the *ambient intelligence* [1] and *pervasive computing* [2] paradigms. In the scenarios envisaged for future smart environments the user needs to manage electronic information easily by having complete access to time-sensitive data, regardless of physical location.

Short-range wireless technology will play a key role in scenarios where "everybody and everything" is connected by different types of communication links: human to human, human to machine, machine to human, and machine to machine. While the majority of human-to-human information exchanges are still by voice, a rapid increase in data transfers is observed in other types of links as manifested by the rising need for location-aware applications and video transfer capability within the home and office environments. In the future, we expect the need for even higher data rates to develop jointly with a flourishing increase in large numbers of low-rate wireless devices embedded in common appliances, sensors, beacons, as well as identification tags, spontaneously interacting in ambient intelligence networks. Against this background, the commercialization of wireless devices based on the principles of ultra-wideband (UWB) radio technology (UWB-RT) is widely anticipated, given the recent endorsement by U.S. regulators [3]. UWB-RT could play an important role in

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the realization of future pervasive and heterogeneous networking. This article discusses the application potential and challenges associated with deploying devices based on UWB-RT as well as their advantages in terms of spectrum efficiency and usage models. The challenges ahead in terms of regulations and standardization are exposed. Careful consideration is also given to the work required to define a UWB physical layer (PHY) that matches the needs for minimal cost and low power consumption while supporting efficient medium access control (MAC) mechanisms and allowing ad hoc communication over multiple hops and seamless access to the backbone networks.

Drivers in the Transition to Heterogeneous Networks

The steep growth in demand and deployment of WLANs/WPANs for short-range connections has been driven by the strength of some of the wireless standards within the IEEE 802 family. The success story of IEEE 802.11 (a, b, g) and Bluetooth products, and the imminent arrival of ZigBee (IEEE 802.15.4) and IEEE 802.15.3 products (see Table 1 for details on these wireless standards) are indicative of the high potential and great market demand for wireless connectivity. But today's short-range networks operate mainly in indoor environments in standalone mode, with a nearly nonexistent integration into the fixed wired and wireless wide-area infrastructures. Furthermore, new and increasingly challenging requirements constantly emerge from the user side: availability of high-rate data access at any time and in any place, long battery life, boundaryless mobility, intelligent and context-aware devices, and applications offering availability of undisrupted service across different networks. Many of these requirements frequently contrast with the reality of radio system engineering, where frequency resources are scarce, in high demand, and incompatible worldwide. Often a device's development is driven by cost more than its function and efficiency, and the deployment of very-high-data-rate services is strongly limited by insufficient bandwidth resources.

The lack of available spectrum to support the growing number of wireless devices is well known, although the reasons for this threat appear mainly to be an artifact of how spectrum resources have been allocated and managed up to now. Due to an increasing need for services with ever growing bandwidth demand but very limited free spectrum available in the industrialized regions of the world, alternative approaches to today's notions of spectrum resources are necessary [4].

UWB Spectral Efficiency

In the short-range application space, UWB-RT can drive the potential solutions for many of today's problems identified in the areas of spectrum management and radio systems engineering. The novel and unconventional approach underlying the use of UWB-RT is based on optimally sharing the existing radio spectrum resources rather than looking for still available but possibly unsuitable new bands. This disruptive idea has recently received legal adoption by the regulatory authorities in the United States [3], and efforts to achieve this status have started in both Europe [5] and Asia, particularly Japan and Singapore. It is widely anticipated that UWB-RT will have a sizable impact on the multimedia-driven home networking and entertainment market, and will allow implementation of intelligent networks and devices enabling a truly pervasive and user-centric wireless world [4].

A generic definition used within the FCC's *First Report and Order* [3] and widely accepted by the industry defines a UWB device as any device emitting signals with a fractional bandwidth greater than 0.2 or a bandwidth of at least 500 MHz at all times of transmission. The fractional bandwidth is defined by the expression $2(f_H - f_L)/(f_H + f_L)$, where f_H is the upper frequency and f_L the lower frequency at the –10 dB emission point. The center frequency of the signal spectrum emitted by such a system is defined as the average of the upper and lower –10 dB points (i.e., $f_C = (f_H + f_L)/2$). At the PHY level, UWB communication systems operate by spreading rather small amounts of average effective isotropic radiated power (EIRP) — always less than 0.56 mW (according to FCC masks) — across a very wide band of frequencies relative to its center frequency. This quantity is easily calculated from the imposed power spectral density limit of 75 nW/MHz (–41.3 dBm/MHz) between 3.1 GHz and 10.6 GHz, as per FCC (and draft ETSI) spectral masks shown in Fig. 1. Inherent in this UWB definition is a high temporal resolution that not only allows the design of radios with much lower fading margins than classical narrowband systems, but also enables precision ranging capabilities combined with data transmissions.

The potential classes of UWB devices are many, ranging from imaging systems (ground-penetrating radar, wall-imaging systems, medical systems, and surveillance systems) to vehicular radar systems, and communications and measurement systems. They all have high spectrum efficiency potential in common, as stated in [3]: "With appropriate technical standards, UWB devices can operate using spectrum occupied by existing radio services without causing interference, thereby permitting scarce spectrum resources to be used more efficiently."

Further spectrum efficiency can be achieved by applying ad hoc networking concepts between the nodes of a WBAN/WPAN network. As an example, using multihop routing, UWB transmitters could reduce their power emissions and thus also their covering area; this in turn would allow a larger number of transmitters to operate simultaneously in the same given area, yielding increased spectral reuse and resulting in higher capacity per area. Building dynamic ad hoc networks on demand could be particularly effective in combination with the use of spectrum overlay and reuse techniques (Fig. 2). Frequency reuse naturally leads to increased spectral efficiencies when measured in terms of spatial capacity (ratio of a cell's aggregate data rate and the coverage area [(b/s)/m^2]). Because a system's maximum transmission range scales inversely with data rate, the cost of "continuous and every-

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Characteristic	IEEE 802.15.4	Bluetooth	IEEE 802.11b	IEEE 802.11g+	IEEE 802.11a	IEEE 802.15.3+	UWB+ HDR
Standard version/status	IEEE approved	V 1.1 (Low-Rate)	IEEE approved	Draft	IEEE approved	Draft	Draft IEEE 802.15.3a
Max. data rate	250 kb/s; 40 kb/s; 20 kb/s	1 Mb/s	11 Mb/s	54 Mb/s	24 Mb/s mandatory; 54 Mb/s optional	11 Mb/s (QPSK) – 55 Mb/s (64 QAM) mandatory: ≥ 22 Mb/s	110 Mb/s (10m) 200 Mb/s (4m) (mandatory) (higher data-rate might optionally apply)
Max. distance	30 m	10 m	100 m	100 m	50 m	10 m	10 m
Frequency allocation	868–868.6 MHz; (ISM EU) 902–928 MHz; (ISM US) 2400–2483.5 MHz (ISM)	2.4 GHz (ISM)	2.4 GHz (ISM)	2.4 GHz (ISM)	5-GHz UNII (5.15 – 5.35 + 5.725 –5.825) GHz	2.4 GHz (ISM) 2.4–2.4835 GHZ	3.1–10.6 GHz
Channel bandwidth	0.3 MHz; 0.6 MHz (2 MHz spacing); 2 MHz (5 MHz spacing)	1 MHz	25 MHz	25 MHz	20 MHz	15 MHz	Min. 500 MHz Max. 7.5 GHz
Number of RF channels	1; 10; 16	79	3	3	12 U.S. 8 EU 4 Japan	5	(1–15)
Modulation type	BPSK; OQPSK	GFSK	11Mbaud QPSK (CCK coding)	OFDM 64 + CCK (legacy)	COFDM BPSK, QPSK, 16 QAM	DQPSK 16/32/64 QAM	BPSK, QPSK
Spreading	DS-SS	DS-FH	CCK	OFDM	OFDM	—	(Multiband)
Maximum allowed RF power	US 1W +6dB antenna gain; (FCC 15.247); EU (868 MHz) ERC70-03E: 25mW if duty cycle < 1% in 1 hour; (2400 MHz) ETSI 300-328: 20 mW[1] (2 MHz channels @ 10 mW/MHz) Japan 10 mW/MHz	0 dBm 20 dBm	US 30 dBm (PC needed for emissions> 20 dBm) EU 20 dBm Japan 10 dBm	US 30 dBm (PC needed for emissions >20 dBm) EU 20 dBm Japan 10 dBm	50 mW; 250 mW; 1-watt (depending on the used channels within the band)	US 50 mV/m (@3m, 1 MHz res. bandwidth) (47 CFR 15.249) EU 100 mW[2] EIRP (ETS 300–328) Jap 10 mW (ARIB STD-T66)	–41.3 dBm/MHz (max. average EIRP over entire band = 0.562 mW) (FCC First Report and Order; Part 15 ET Docket 98-153)
Required receiver sensitivity	–85 dBm PER<1%	–70 dBm BER < 10^{-3}	–76 dBm BER<10^{-5} FER = 8×10^{-2}	From –76 dBm (22 Mb/s) to –74 dBm (33 Mb/s) FER = 8×10^{-2}	From –82 dBm (6 Mb/s) to –65 dBm (54 Mb/s) BER < 10^{-5}	From –82 dBm (DQPSK) to –68 dBm (64 QAM)	—
Approx # PHY power consumption	< BT	BT (~ 40–100 mW)	~4BT	~4BT	~6BT	—	(~2–3BT)
Approx cost#	~0.5 BT	BT (~ 5$)	~4BT	~4BT	~5BT	—	(~1–2BT)

• Acronyms used: BT = reference Bluetooth device, CCK = complementary code keying (CCK), orthogonal frequency-division multiplexing (OFDM), COFDM = coded OFDM, ISM = industrial, scientific, medical, PC = power control, PSDU = PHY service data unit (payload), UNII = unlicensed national information infrastructure.
+ These specifications are currently (April 2003) under drafting. All parameters mentioned are speculative, in particular some of those referring to IEEE 802.15.3a, which is in its early stages of discussion.
# Parameters referring to power consumption and cost can vary dramatically from design to design; these numbers are only to be considered as rough indications.
[1] IEEE 802.15.4 EU general equipment plans to use 1–10 mW. [2] IEEE 802.15.3 EU general equipment plans to use 8 dBm.

Table 1. *Summary of characteristics of some leading WLAN/WPAN standards.*

where at all times" coverage increases sharply with data rate. Thus, short-range radio systems covering relatively small areas (micro/picocells), particularly those based on UWB-RT, will be important enablers of future high-spatial-capacity networks. Besides the ability to potentially operate worldwide across bands occupied by existing narrowband systems, UWB radio systems offer additional flexibility in that they can maintain a cell's spatial capacity by adapting to either a large number of low-rate nodes or a smaller number of high-rate nodes, depending on the requirements of the application.

Potential Applications of UWB-RT

While the commercialization of UWB-RT is just beginning, the technology offers significant potential for the deployment of short-range communication systems supporting high-rate applications and lower-rate intelligent devices embedded within a pervasive and personal wireless world. For example, Fig. 3 indicates that FCC-compliant UWB radio systems, using simple modulation and appropriate coding schemes, can transmit at information rates in excess of 100 Mb/s over short distances (upper left region), an operational mode here defined as *high data rate* (HDR). Alternatively, UWB radios can trade a reduced information rate for increased link range, also shown in Fig. 3 (lower right region), potentially combined with accurate location-tracking capabilities, offering an operational mode defined here as *low data rate and location tracking* (LDR/LT). The two complementary usage regions indicated in Fig. 3 are unique to UWB radio systems as they can be implemented based on very similar architectures with an unprecedented degree of scalability.

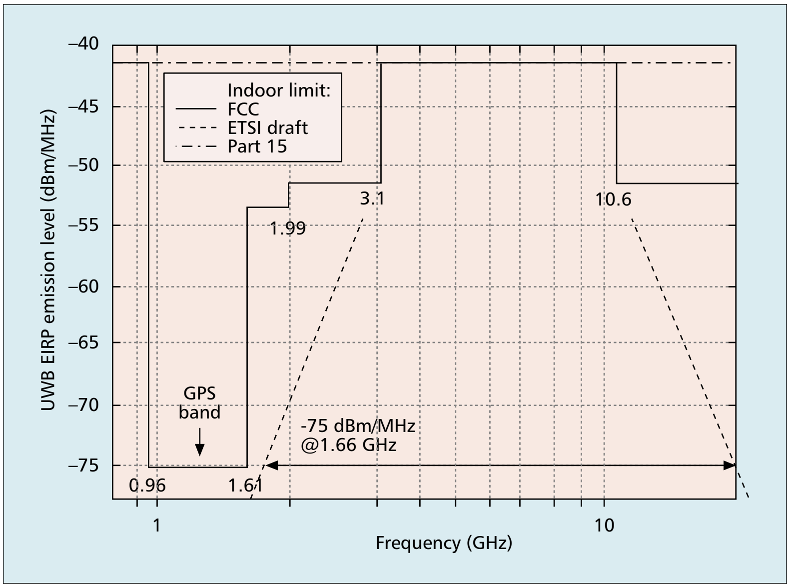

Figure 1. *FCC First Report and Order and ETSI draft spectrum mask for transmissions by UWB communication devices in indoor situations.*

A number of practical usage scenarios well suited to UWB have been identified (Fig. 4). In these scenarios system implementations based on UWB-RT could be beneficial and potentially welcome by industry and service providers alike:

- *High-data-rate wireless personal area network* (HDR-WPAN)
- *Wireless Ethernet interface link* (WEIL)
- *Intelligent wireless area network* (IWAN)
- *Outdoor peer-to-peer network* (OPPN)
- *Sensor, positioning, and identification network* (SPIN)

The first three scenarios assume a network of UWB devices deployed in a residential or office environment, mainly to enable wireless

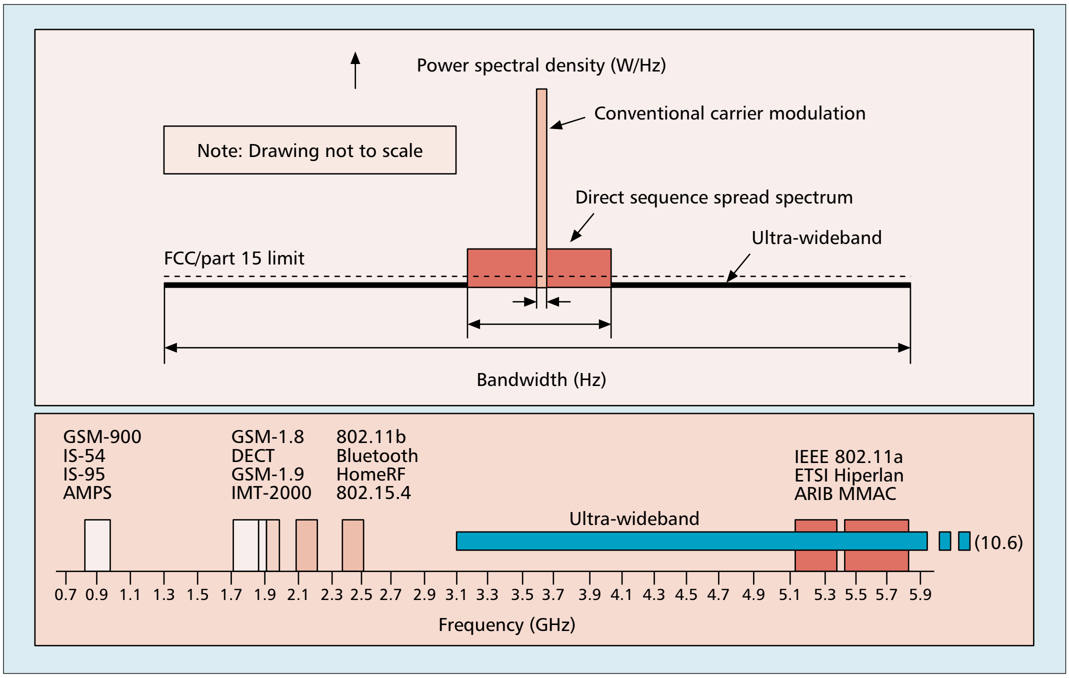

Figure 2. *Ultra-wideband radio technology: bandwidth comparison of different types of wireless systems (top); spectrum overlay principle (bottom).*

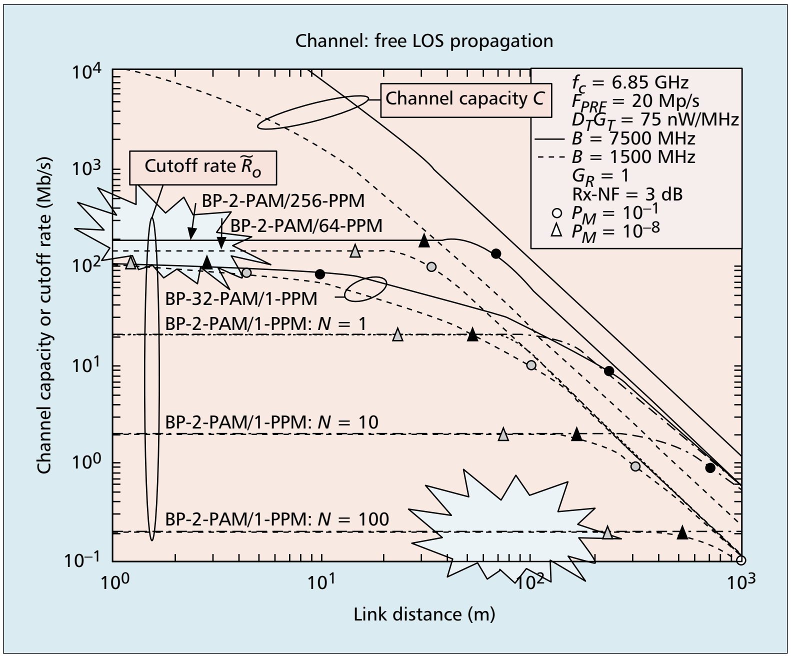

Figure 3. *Potential and complementary application regions for UWB-RT.*[1]

[1] *This figure shows the Shannon capacity,* C*, and the (symmetric) cutoff rate,* $\tilde{R}_o$*, for signals of different bandwidth (*B*), 1.5 GHz and 7.5 GHz, transmitted over the line-of-sight (LOS) additive white Gaussian noise (AWGN) channel. The following main system parameters and acronyms have been used: BP-*n*-PAM/*m*-PPM: biphase,* n*-level pulse amplitude modulation, and* m*-slot pulse position modulation (the chosen modulation schemes do not necessarily imply an optimal choice);* N*:* N*-fold pulse repetition coding;* f_C*: signal's spectral center frequency determining LOS path loss;* F_{PRF}*: pulse repetition frequency;* D_T G_T*: transmitted effective isotropic radiated power (EIRP) spectral density* G_R*: receiver antenna gain (unity); Rx-NF: receiver noise figure measured in dB;* P_M*: symbol error rate of a maximum likelihood detector (without coding). Note: A system's symbol error rate can be made arbitrarily small as long as the transmission's information rate is less than the indicated cutoff rate,* $\tilde{R}_o$*.*

video/audio distribution for entertainment, control signals, or high-rate data transfers. The fourth scenario presents a deployment in outdoor peer-to-peer situations, while the fifth takes industry and commercial environments into account. The identification of common elements among the scenarios listed and the optimization of system cost, coverage range, data rate, localization precision, battery burden, and level of adaptability to channel conditions are still tasks ahead. But assuming adherence to FCC regulations in principle, some preliminary considerations can be given to the individual scenarios.[2]

High Data Rate Wireless Personal Area Network

We define HDR-WPANs as networks with a medium density of active devices per room (5–10) transmitting at up to 100–500 Mb/s data rate[3] at a distance between 1 and 10 m, mainly based on a peer-to-peer topology and using a relay/bridge to the outside world based on existing (either wireless or cable) standards. There is a need to carefully define the interface and adaptation between local and remote modes, as the outside world may be limited to accept only lower data rates (e.g., WAN).

[2] *While the scenarios introduced in this paragraph are quite descriptive, their names are somewhat artificial and thus might disagree with some of the names used in other publications for similar scenarios.*

[3] *The term* data rate *as used here and elsewhere in this article follows the definition of the data rate as calculated at the physical layer service access point (PHY-SAP) level of a device with a packet error rate of 8 percent for 1024-octet frame bodies as per the IEEE 802.15.3a draft specification.*

Wireless Ethernet Interface Link

This is an extension of the concept of HDR transmission to extremely high data rates (e.g., 1 Gb/s, 2.5 Gb/s), probably only over rather short distances (i.e., at most a few meters). The WEIL concept could satisfy a specific demand:

- From PC manufacturers that calls for a direct wireless replacement for Ethernet cables
- From consumer electronics firms asking for a high-quality wireless video transfer capability between a PC and an LCD screen, such as for wireless digital video interface (DVI).

This latter application is the most demanding, and much research is still needed to determine whether it is feasible with current transmission power limits.

Intelligent Wireless Area Network

IWANs are characterized by a high density of devices in a domestic or office environment, covering distances over 30 m (Fig. 5). The main requirements for the devices are: very low cost (<1 dollar/unit) and very low power consumption (e.g., 1–10 mW) to provide users with access to intelligence distributed around the home/office (e.g., automated smart appliances). Device capabilities will include accurate location tracking in support of context-aware services (e.g., child and/or asset tracking, alarm zones, phone auto-modes, electronic virtual guides) that is not readily realizable with the current generations of narrowband short-range networks. In this scenario an eventual wireless last mile and/or other interconnections to the outer world could be used to send alarms and control signals, and/or remotely check the status of sensors around the home.

Outdoor Peer-to-Peer Network

This is a network of UWB devices deployed in outdoor areas, mainly to respond to new market demands for PDA linkup and information exchange, digital kiosks for fast download of newspaper text, photographs, automatic video rental, or sale distribution systems. To what degree the specifics of an application scenario chosen will determine whether the OPPN architecture is centralized or distributed is an open research problem. It should also be noted that today's UWB regulations valid in the United States and the envisaged generic UWB standard to be adopted in Europe severely constrain any deployment of UWB devices supporting outdoor scenarios. However, this situation might change, because it is anticipated that future UWB usage regulations will likely follow an evolutionary path to an even greater extent than that experienced for other wireless services in the past.

Sensor, Positioning, and Identification Network

A SPIN is a system characterized by a high density (e.g., hundreds per floor) of devices (intelligent sensors or tags) in industrial factories or warehouses transmitting low-rate data combined with position information (e.g., data rate greater than

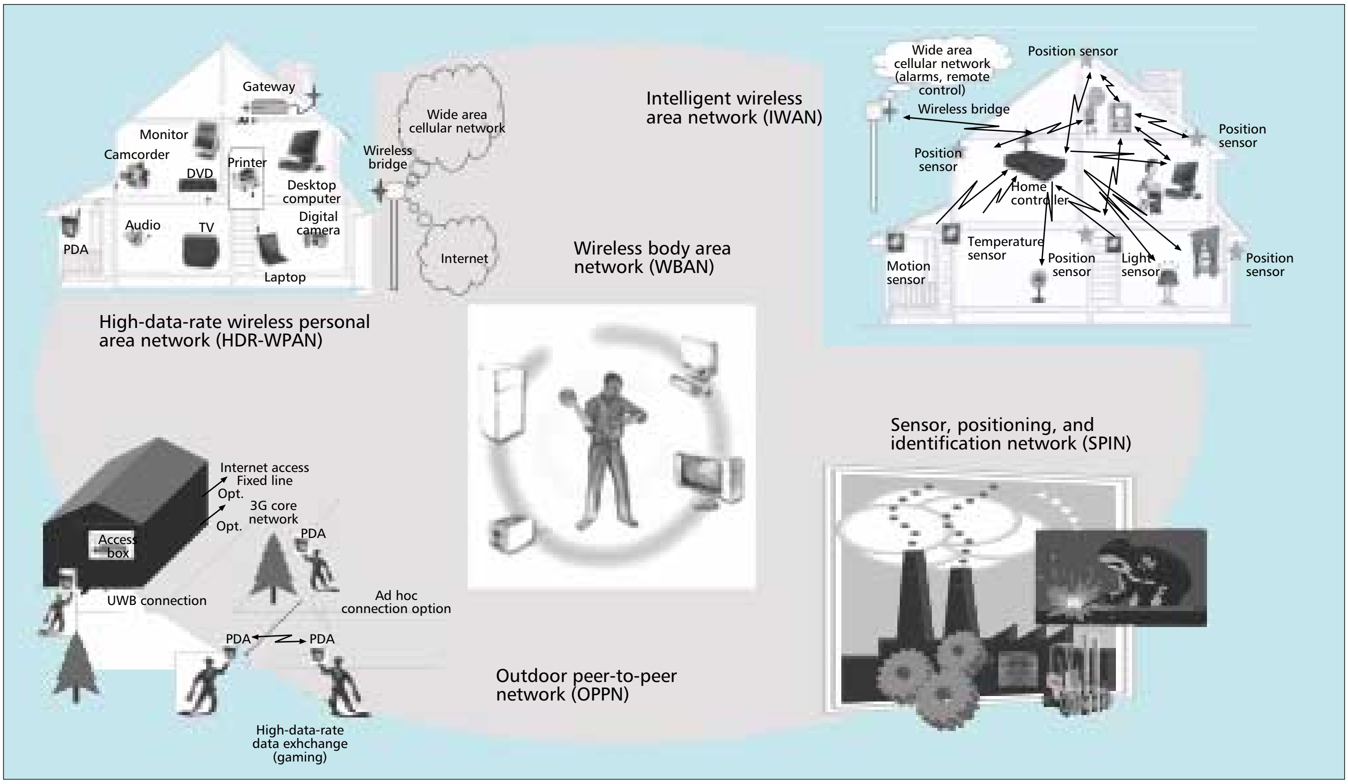

Figure 4. *Envisaged scenarios for future UWB radio applications: HDR-WPAN, IWAN, SPIN, OPPN, and WBAN (see text).*

several tens of kilobits per second and position accuracy well within 1 m). SPIN devices operate over medium to long distances (typically ~100 m) between individual devices and a master station with a typical master-slave topology. In industrial applications, SPINs require a high level of link reliability and adaptive system features to react to the dynamically changing and very challenging interference and propagation environment.

An important role that UWB technology will play is the provisioning of effective services responding to user demands. Keeping this in mind, the schematic breakdown of scenarios and development of separate networks covering each of the cases under analysis is not sufficient to satisfy the expectations of the users and provide concrete advances over narrowband systems. A significant target is therefore the capability for seamless coexistence, interoperability, and integration among different scenarios as well as with incumbent wireless communication protocols (e.g., IEEE 802.11 or cellular WANs) to achieve truly *heterogeneous* networking. Thus, the design of efficient bridges, automatic roaming mechanisms, and adaptation of the data link will be an essential aspect in any future R&D effort in this area.

Regulation and Standardization

Given the innovative nature of systems based on UWB-RT, a considerable amount of work will be necessary to lead the way to radio solutions that are compatible with current incumbent services and concurrently guarantee interoperability among devices from different manufacturers. The particularly novel nature of frequency sharing between services of different providers to maximize spectrum usage has absorbed considerable resources in the past 10 years in the United States and resulted in a first ruling by the FCC [3]. The positive legal actions by the FCC have spurred similar efforts in Europe and more recently also in Asia.

In Europe, the European Telecommunications Standards Institute (ETSI) has been working for more than two years to establish a legal framework for the deployment of license-free UWB devices in the old continent. The work is pursued by Task Group 31 (TG31) of the Technical Committee EMC and Radio Spectrum Matters (TC-ERM). In close cooperation with the European Conference of Postal and Telecommunications Administrations (CEPT) SE24, ETSI is considering the best options for this emerging technique and its frequency sharing with other services (see Fig. 1 for a very preliminary draft indoor mask for UWB communications devices).

In Asia, efforts are underway in Japan and Singapore. In September 2002, Japan's Information and Communication Technology Sub-Council submitted its initial findings on UWB to the Ministry of Public Management, Home Affairs, Post and Telecommunications (MPHPT), preparing the ground for an UWB ruling. In addition, Japan's Communications Research Laboratory (CRL) pursues a project with key industrial partners to develop commercially viable systems based on UWB-RT. In early 2003, Singapore's Infocomm Development Authority (IDA) created a *UWB friendly zone* (UFZ) within a specific location in Singapore to permit IDA-led technology trials and give UWB developers an opportunity to conduct realistic field experiments with power levels up to 6 dB above the FCC limit.[4]

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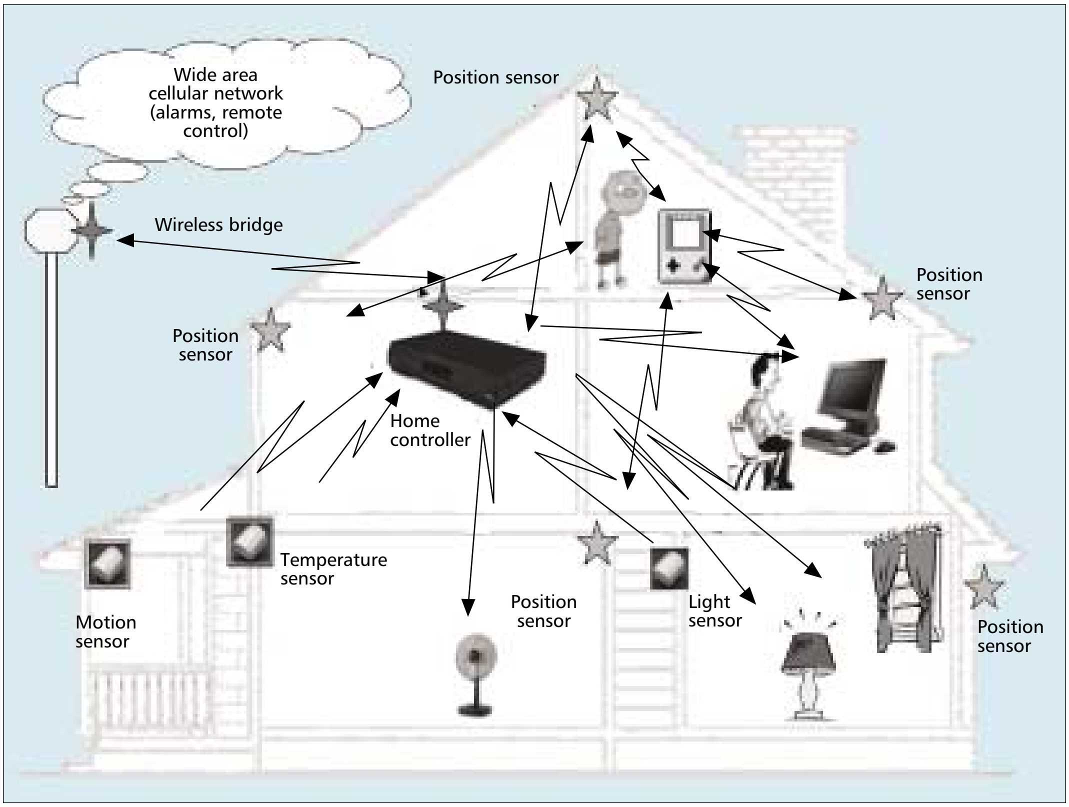

Figure 5. *The scenario of an indoor IWAN.*

UWB-RT offers great promise and potential, but at the same time poses an even greater regulatory challenge. Although FCC-compliant UWB signal sources currently are allowed to emit only rather small amounts of RF power, limiting communication distances to fairly short distances, most of this radiation occurs inside spectral bands already allocated to other services. Whereas few question the interference potential of a *single* UWB signal source in a typical home or office environment, many others express great concerns should UWB devices proliferate and become truly ubiquitous. It is feared that the simultaneous operation and *aggregation* of several hundred UWB transmitters within a confined area may pose a risk of harmful interference to incumbent services, such as navigation, rescue, and communications, or fixed wireless access services [6]. The UWB community expends great effort to address these legitimate concerns by proposing and designing systems that prevent interference under all practical and reasonable conditions. However, only a large research effort, and scrutinizing analysis and measurements will be able to help establish the most appropriate set of rules for this capable yet disruptive spectral overlay technology.

The conservative masks approved in the FCC's *First Report and Order* [3] and an even more restrictive set under development for Europe by the ETSI ERM TG31a should ensure that emerging UWB radio products will be safe, while progressive revisions will eventually refine and evolve the specifications. In Europe, efforts are underway to protect all potentially affected services, and many of the service providers are actively engaged in the technical efforts within CEPT SE24 group, for example, the fixed wireless access (FWA) operators (with affected bands 3.5 GHz, 3.6–4.2 GHz, 4.4–5.0 GHz), the cellular system manufacturers (bands: 915 MHz, 1800–2100 MHz) and the space scientific community (bands 406–406.1 MHz, 1400–1427 MHz, 1544–1545 MHz, 5250–5460 MHz).

Very broadly supported PHY and MAC level industrial standards will be a prerequisite for a potentially successful deployment of UWB-RT. Moreover, it is likely that standardization efforts will also be necessary at the (ad hoc) network management level to enable flexible integration of a variety of participating mobile nodes and ensure interoperability between different devices. Although one can argue over the degree to which the need for standardization depends on the intended application, the future emergence of UWB-RT should be considered a unique opportunity to develop and standardize PHY/MAC and networking functions for short-range wireless systems that combine data communication and positioning capabilities.

Within the IEEE, the recently established Task Group 3a (TG3a) focuses on the definition of a PHY alternative (Alt-PHY) to 802.15.3 (details in Table 1) likely to be based on UWB-RT. This newly defined Alt-PHY (IEEE 802.15.3a) will respond to consumer demands in the area of multimedia distribution (i.e., HDR mode) and will work with an already designed MAC (IEEE 802.15.3) to provide a unique combination of standard features and new technology, with approval expected by early 2005. The adoption of predefined MAC layers on top of the newly defined PHY (e.g., IEEE 802.15.3

[4] *Details on these regulatory authorities and scientific groups and their initiatives can be found on these Web sites:*
FCC: http://www.fcc.gov
ETSI ERM: http://portal.etsi.org
CEPT: http://www.ero.dk
MPHPT: http://www.soumu.go.jp/joho_tsusin/eng/index.html
CRL: http://www.crl.go.jp
IDA: http://www.ida.gov.sg

over 802.15.3a) will characterize the first phase of commercial development of consumer UWB-RT applications. Although such an approach might reduce the overall system efficiency and potential level of QoS, it may be a sensible compromise, helping to expedite the commercial deployment of UWB-RT.

In parallel with the standardization effort and following the successful path of branding a wireless standard as demonstrated by the WiFi® association, a sister industry association called WiMedia® was formed in 2002 to build a brand image, and establish test and interoperability compliance procedures for the 802.15.3 standard under development by the IEEE. In addition, a new and complementary interest group to IEEE 802.15.3a was recently formed within IEEE 802.15.4 (IG4a) to analyze the potential for a standard specifying a low-rate, low-power, and low-cost WPAN technology based on UWB-RT.

TECHNOLOGY CHALLENGES

Short-range wireless systems based on narrowband carrier modulation are often inadequate or incapable of providing sufficiently high data rates to transmit video over air and/or accurate information about a mobile terminal's location to support location-aware applications or routing. In today's marketplace we see a growing need for these capabilities. It remains an objective of ongoing as well as future research (e.g., [7]) to determine the practical limits of achievable spatial capacity, measured in terms of a network's aggregate data rate in bits per second for each cell area in square meters, and introduce other relevant parameters to characterize system performance and spectral efficiency of UWB radio devices. For example, an empirical performance measure (M) has been proposed[5] based on comparing the ratio of a system's spatial capacity (C_S) and the product of DC power drawn from the battery (P_{DC}), cost ($P_\$$), and volume size (form factor) of a device (V), as indicated by the following formula:

$$M = \frac{C_S}{P_{DC} P_\$ V}, \left[\frac{(b/s)/m^2}{W\$m^3}\right].$$

Many open questions also exist in the areas of mutual interference between UWB devices, and required and achievable level of QoS. Concerning location awareness, it will be necessary to determine the required level of accuracy for any given application and whether this level of quality can be maintained under varying channel and network load conditions.

Technical challenges also exist in the areas of modulation and coding techniques suited for UWB radio systems. Originally, UWB-RT has been applied for military purposes, where achieving high capacity in terms of supported number of users was not necessarily a main objective. However, large multi-user capacity becomes very important in commercial applications. Coding and modulation are known to be some of the most effective means to improve on a system's multi-user capacity. Adaptive modulation methods (e.g., dynamically changing the modulation used in each subband, if a multiband approach is followed) and channel coding schemes will have to be devised that take into account the specific time domain properties of the UWB radio channel. Also, although the average EIRP appears to be very low in UWB radios (strictly less than 0.56 mW [3]), the required peak power in a given short time interval might become relatively large for certain pulse-based modulations. Thus, adequate characterization and optimization of transmission techniques (e.g., adaptive power control, duty cycle optimization) will be required. To cope with difficult signal propagation environments (e.g., industrial and manufacturing or commercial areas), advanced technologies such as UWB multiple-input multiple output (MIMO) systems may be able to provide the required high degree of link reliability and (rate) adaptation capability [8]. Unlike narrowband radio systems, UWB systems suffer much less from signal fading effects because the extremely narrow pulses propagating over different paths cause a large number of independently fading signal components that can be distinguished due to the high temporal resolution, resulting in significant multipath diversity. UWB MIMO systems also cope better with adverse intersymbol interference (ISI) and interchannel interference (ICI) in the time domain, because of the very favorable auto- and cross-correlation properties of the received signals and the capability to simply adapt the pulse repetition frequency to the prevailing channel delay spread [7, 8].

In addition, although UWB systems feature a certain inherent robustness to multipath effects, they are not entirely immune to them. For example, in situations where there is an excessive ratio of link distance (d) to antenna height, the time difference between the LOS and the reflected signal components can be substantially shorter than the duration of a pulse. This may result in signal losses according to the $(d/d_0)^n$ attenuation model, where for non-LOS conditions (values of $n < 2$ are possible in LOS configuration due to constructive multipath contributions) and d_0 is a reference distance. Extreme signal propagation situations can arise in indoor environments where the numerous multipath components associated with each transmitted pulse result in propagation delay profiles that last tens and even hundreds of nanoseconds. The ISI occurring from these not so uncommon multipath conditions severely limit the maximum achievable data rate of a system, unless an effective method can be found to mitigate these effects. In the case of fast pulse modulation techniques (e.g., PPM), the cost for realizing effective equalizers might be very high, in terms of both gate count and power consumption. This problem is much less pressing when using low pulse repetition systems (e.g., as in a multiband approach), where the system complexity is instead challenged by the need for multiple parallel detectors or higher-order modulations.

A particularly challenging area at the PHY level today appears to be antenna design and implementation for UWB radio devices. Generally, portable communication devices require small and preferably unobtrusive antennas that can be integrated into miniature devices and are capable of operating effectively under varying

Short-range wireless systems based on narrowband carrier modulation are often incapable of providing sufficiently high data rates to transmit video over air and/or accurate information about a mobile terminal's location to support location-aware applications or routing.

[5] *See also: P. Gandolfo, "XtremeSpectrum — SG3a CFA response," IEEE P802.15 ALT PHY Study Group, Doc. 02031r0P802-15_SGAP3-CFAReaponseAltPHY.ppt (http://grouper.ieee.org/groups/802/15/pub/), Jan. 14, 2002.*

The design and implementation of effective antennas is more challenging for UWB radio systems than for conventional narrowband systems given the large bandwidths, linearity requirements, and variable conditions of operation.

environmental conditions, often in near-field propagation conditions (e.g., near objects, or carried on or close to the body). The design and implementation of effective antennas is more challenging for UWB radio systems than for conventional narrowband systems given the large bandwidths, linearity requirements, and variable conditions of operation.

A further aspect not yet fully investigated relates to the deteriorating effects of in-band interference in UWB receivers that originates from other radio signals, be they in near- or far-field proximity. The problem of nearby interference is not only of academic interest, considering that UWB devices might be integrated into mobile platforms that make simultaneous use of a variety of other radios. Thus, the very advantage provided by the fact that UWB devices emit an extremely low power spectral density (PSD), as a result of the excessive signal bandwidth, potentially yields increased susceptibility to noise and interference in the UWB receiver. Similar effects may occur in areas with a large concentration of active UWB devices. This raises questions concerning harmful compound effects of multipath propagation and cross-device interference phenomena as well as how to initiate and maintain synchronization at the receiver and network levels.

To improve adaptive modulation methods, it would be necessary to identify methods for measuring prevailing noise levels and interference characteristics on the fly to be able to apply suitable interference rejection schemes. For example, narrowband signals tend to interfere at levels tens of dB above the received UWB signal level, leading to challenging requirements on the dynamic range of the UWB receiver. The impact of such a high dynamic range on the analog front-end and/or digital baseband of a UWB receiver needs to be analyzed to realize adequate trade-offs between hardware cost, dynamic range requirements, power consumption, and receiver performance. The excessive bandwidth of UWB is likely to require dedicated custom designs for specific circuit components (e.g., wideband LNA and power amplifier, fast analog-to-digital conversion).

Finally, the use of new and advanced semiconductor technologies in UWB system realizations needs to be explored, such as microelectromechanical systems (MEMS) and silicon on insulator (SOI) techniques as well as nonlinear analog circuit and component design techniques (e.g., efficient integration of tunnel diodes on silicon is an open problem). These techniques could potentially provide interesting solutions to problems such as excessive clock speed, synchronization latency, and power consumption; their successful exploitation may become a crucial factor in future developments and applications of UWB-RT.

CONCLUSIONS

UWB-RT has the potential to become a viable and competitive wireless technology for short-range high-rate WPANs as well as lower-rate and low-power-consuming low-cost devices and networks, with the capability to support a truly pervasive user-centric and thus personal *wireless world*. UWB-RT's innovative but somewhat disruptive spectral overlay technique can become the basis for new short-range wireless services and applications within the future heterogeneous network world, where seamless transition from one network to another will be transparent to the user. This article emphasizes some of the merits and challenges related to the use and commercial deployment of UWB-RT. An overview of the current status of worldwide UWB regulations and standardization together with an introduction to potential future usage scenarios and applications are given. While the technical, economical, and regulatory challenges ahead are probably still as numerous as the promises this intriguing wireless technology appears to offer, dedicated research and development efforts combined with a viable global regulatory framework will further the chances of UWB-RT to become the new enabler for intelligent short-range networking applications and services within the next decade.

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