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ULTRA-WIDEBAND SYSTEMS FOR DATA COMMUNICATIONS

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ABSTRACT

Ultra-Wideband[1] (UWB) is a radio transmission scheme that uses extremely low power pulses of radio energy spread across a wide spectrum of frequencies. UWB has several advantages over conventional continuous wave radio communications including potential support for high data rates, robustness to multipath interference and fading. We present an overview of UWB technology and its use in data communications and networking. We look at design considerations for UWB based networks at various layers of the protocol stack.

1. INTRODUCTION

Ultra-Wideband [1–6] — also known as baseband or impulse radio — is a carrier-free radio transmission that uses narrow, extremely low power pulses of radio energy spread across a wide spectrum of frequencies. UWB has recently gained a great deal of interest due to the recent Federal Communications Commission (FCC) Report and Order which allocates the UWB band — 7.5 GHz of unlicensed spectrum for indoor and outdoor communication applications. UWB communications are required to have a –10 dB fractional bandwidth of more than 20% or a –10 dB bandwidth of more than 500 MHz [7]. It is important to note that the FCC has not defined a specific modulation scheme to be used. UWB systems offer the promise of high data rate, low susceptibility to multipath fading, high transmission security low prime power requirements, low cost, and simple design [1,2,5,6]. UWB has been used in military applications for the past several years for ground-penetrating precision radar applications and secure communications [3,8]. For the past few years, UWB has been developed for commercial applications [1,2,5,6]. With the recent FCC [7] report and order for the use of UWB technology, there has been an added impetus to this endeavor. Other notable UWB applications include collision avoidance radar, tagging/identification, geolocation [9] and data communications in personal area networks (PAN) and local area network (LAN) environments.

UWB presents a great opportunity for data communications for today's media-rich consumer electronics and home entertainment systems that run on battery powered handheld devices. It can form the basis of a low cost, low power and very high data rate solution as a wireless "cable replacement" technology for computer-to-peripherals, peripherals-to-peripherals and digital home networking applications. A very useful attribute of UWB technology is its ability to perform precision geo-location which can aid in ad-hoc or mesh networking where the operations of the mobile hosts benefit by knowing the location of the other hosts. UWB technology promises to fill the void left by established standards like Bluetooth and 802.11a/b/g.

There are several future challenges to the wide adoption of UWB for wireless data communications including the infancy of the technology in the commercial arena, lack of reliable channel models, the early stages of standardization effort and lack of low-cost system on chip (SoC) implementations. In this paper, we look at UWB technology for data communications and inside a UWB physical (PHY) layer characteristics. We also briefly introduce other related wireless standards such as 802.11 [10], 802.15.3 [11–13] Bluetooth [14], HomeRF [15] and HIPERLAN [16] and present a brief synopsis of the regulatory effort worldwide with special emphasis on the FCC. We also present the design considerations for UWB based data networking.

2. ULTRA-WIDEBAND TECHNOLOGY

The basic waveform that employed in a UWB system is an approximation to an impulse, such as that shown in Fig. 1. The short duration of the pulse is associated with large inherent bandwidth; hence, the nomenclature "Ultra-Wideband". Typical attributes of UWB waveforms are summarized in Table 1.

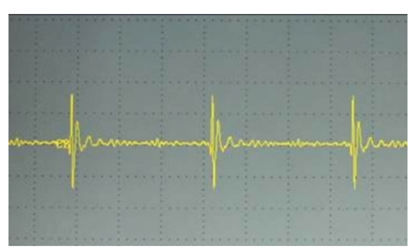

Fig. 1. UWB waveform example.

[1]According to the FCC, UWB communication systems are required to have a –10 dB fractional bandwidth of more than 20% or a –10 dB bandwidth of more than 500 MHz.

Table 1: Characteristics of Typical UWB Systems

Fractional Bandwidth	> 20%
Pulse Width	0.1–2 ns
Pulse Repetition Frequency	1 kHz–2 GHz
Average Transmitted Power	< 1 mW

The high spectral content of the UWB waveform gives rise to one of the primary advantages UWB operation for communications where a UWB system is robust against multipath fading [17] and narrowband interference [18]. In multipath fading, where the transmitted radio frequency (rf) signal can reflect off objects in its transmission path and can cause destructive interferences at the receiver, a loss of reception can occur. This effect is particularly problematic indoors where there are many reflecting surfaces. In the frequency domain, multipath is shown as frequency selective fading. Because UWB communications systems spreads the transmitted data over a broad frequency band if destructive interference occurs at a specific frequency, whether due to multipath or narrowband interference, the information can still be recovered over the good frequencies.

UWB implementations can provide low complexity, low cost solutions [19], thus enabling vast deployments of the technology. A critical component that reaffirms a low cost solution is noting that UWB signals, being carrier-less, have greater simplicity over narrowband transceivers and require smaller silicon die sizes [20]. UWB can be designed to achieve very high bit rates while still achieving low power consumption, a feature set which will be exploited by the consumer electronics industry [21]. UWB schemes can further be designed to be very scalable in terms of complexity, bit rate, power consumption, and range.

UWB technology can support many applications. Different UWB modulation schemes offer different advantages for communication, radar, and precision geo-location applications. UWB technology, which operates between 3.1 and 10.6 GHz, intrinsically offers an efficient reuse of precious spectrum by operating stealthily at the noise floor [22]. This UWB system operates at low power, to be compliant with operating under FCC Part 15 emissions, across a wide range of frequencies. As a spread spectrum technology, UWB offers a low probability of intercept and a low probability of detection [8]. Thus, it is particularly well suited for covert military or sensitive usage scenarios [8]. Because UWB signals have extremely short bursts in time (e.g., durations of 1 ns or less) they are suited for precision geo-location applications. Though UWB intrinsically offers the above-mentioned features, application optimization and improvements on these characteristics are left to specific designs and implementations, most notably by careful consideration of modulation schemes.

2.1. UWB System Design Considerations

Several considerations are needed when designing a PAN. First, low power design is necessary because the portable devices within the network are battery powered. Second, high data rate transmission is crucial for broadcasting multiple digi\-tal audio and video streams. Lastly, low cost is a prerequisite to broadening consumer adoption. In addition to these criteria, the UWB system designer must address synchronization and coexistence. Capturing and locking onto these short pulses make synchronization a non-trivial task. Coexisting peacefully with other wireless systems without interference is important; in particular, one needs to pay attention to the 802.11a wireless LANs that operate in the 5 GHz ISM bands.

At the physical layer, additional challenges lie in the transceiver and antenna design. At the transmitter, pulse shaping is required to produce flat and wideband emission in the desired frequency bands. Although new integrated circuits provide less expensive forms of integration, the pulses can be affected by the parasitics from the component and packaging [23]. To accommodate the high data rates, tradeoffs between high and low pulse repetition frequency (PRF) and modulation schemes must be considered. The low PRF system with higher modulation (more bits per symbol) may require a more complex receiver, while the high PRF system with lower modulation may lead to performance degradation for delay spread in the channel. Finally, traditional antenna designs gear towards narrow band systems. To avoid dispersion at the receiver, the new wideband antennas need phase linearity and a fixed phase center [23].

3. UWB STANDARDIZATION AND REGULATORY EFFORTS

There are several standards bodies presently considering, at some level, UWB technologies. The standards body most advanced in the consideration of UWB is study group “a” of IEEE 802.15.3, which was formed in November 2001 [11–13]. A serious effort is well underway to define a UWB channel model, and numerous UWB tutorials have been given. Many hallway conversations talk to a physical layer standard being ratified in 2004 (though there is no formal knowledge or position on this) and will accompany the soon to be approved 802.15.3 Medium Access Control (MAC) which supports quality of service (QoS) for real-time multimedia applications [12]. The technical requirements presently call for bit rates of 110 to 200 Mbps at ranges up to 10 m, with the option to achieve 480 Mbps possibly at shorter distances. The power consumption requirement is presently set at 100 to 250 mW with $10e^{-5}$ bit error rate at the top of the physical layer. Complexity/cost are presently expected to be comparable to Bluetooth and the physical layer is required to support four collocated piconets. Coexistence is presently crucial (e.g., IEEE 802.11a) and the ability to scale the technology is key to a long lasting and widely adopted standard. These technical requirements come from documents that are still being revised; additionally, it is not possible to predict if proposals may fall short of meeting some of the desired requirements.

The United States FCC issued a report and order in the early part of 2002. This landmark decision to permit UWB operation in the 3.1 to 10.6 GHz spectrum under Part 15 emission limits, with some additional restrictions, has catalyzed development and standardization processes as is evident by the sheer number of entities (companies, academic and government institutions) associated with UWB and through the serious efforts of the IEEE 802.15.3 group. The FCC carefully chose the frequency band of operation to be above 3.1 GHz to avoid interfering with GPS and other life critical systems. Furthermore, the FCC ruled that emissions below Part 15 would provide for peaceful coexistence, the ability to have narrowband and UWB systems collocated on a non-interfering basis, because unintentional emissions from devices such as laptops are also limited to Part 15 rules. This ruling makes it possible to have up to 15 UWB frequency bands in the 7.5 GHz allocated unlicensed spectrum [7]. Extensive efforts are being conducted throughout Europe (CEPT, ETSI, and the European Commission), Korea, and Japan (Association of Radio Industries and Businesses, and the Japanese Ministry of Telecommunications).

4. NETWORKING WITH UWB SYSTEMS

There is a significant interest in the ability to perform location determination and tracking of assets and people throughout warehouses, factories, ships, hospitals, business environments, and other buildings or structures. The ability for UWB technologies to operate within such intense multipath environments in conjunction with the ability for UWB to provide very accurate geo-location capability at low cost and long battery life justifies the increasing technological activity in this market [20].

As the rf tags [24] are distributed, it is also recognized that they can be coordinated and networked. To further reduce the cost of the transceivers, position determination can occur at networked computer terminals. Additionally, it is quite conceivable that tag complexity can be further simplified by installing transmitters that chirp periodically [8]. Just as UWB demonstrates many benefits for rf tags, the technology equally lends itself to distributed sensor networks [9]. Sensor network applications include feedback controls systems and environmental surveillance for commercial, industrial, and military applications.

In the data communication area, UWB technology may be used to implement ad-hoc networks. An ad-hoc network [25–27] is characterized by a collection of hosts that form a network “on-the-fly”. An ad-hoc network is a multi-hop wireless network wherein each host also acts as a router. Mobile Ad-hoc NETworks (MANETs) [25–27] are ad-hoc networks wherein the wireless hosts have the ability to move. Mobility of hosts in MANETs has a profound impact on the topology of the network and its performance. Figure 2 illustrates how the various layers of the OSI protocol stack have to operate in order to successfully complete a communication session. We look at some of relevant design issues at the different layers for UWB-based sensor networks and MANETs.

4.1. Design Issues for Layers of the Protocol Stack

There are several design considerations of sensor networks setup (including rf tags) [24]. The sensors typically work on batteries and need be low cost, low power, with LPI/LPD and the ability to do geo-location. All of these requirements are satisfied by a UWB PHY.

The PHY layer [26,27] is a very complex layer which deals with the medium specification (physical, electrical and mechanical) for data transmission between devices. The PHY layer specifies the operating frequency range, the operating temperature range, modulation scheme, channelization scheme, channel switch time, timing, synchronization, symbol coding, and interference from other systems, carrier-sensing and transmit/receive operations of symbols and power requirements for operations. The PHY layer interacts closely with the MAC sublayer to ensure smooth performance of the network. The PHY layer for wireless systems (such as MANETs) has special considerations to take into account as the wireless medium is inherently error-prone and prone to interference from other wireless and rf systems in the proximity. Multipath is important to consider when designing wireless PHY layer as the rf propagation environment changes dynamically with time; frequent disconnections may occur. The problem is exacerbated when the devices in the network are mobile because of handoffs and new route establishment. It should be noted that there is a concerted effort by several UWB companies to muster support for a UWB-based high data rate PHY in the IEEE 802.15.3 working group.

The data link layer consists of the Logical Link Control (LLC) and the MAC sub layers. The MAC sublayer is responsible for channel access and the LLC is responsible for link maintenance, framing data unit, synchronization, error detection and possible recovery and flow control. The MAC sublayer tries to gain access to the shared channel to prevent collision and distortion of transmitted frames with frames sent by the MAC sublayers of other nodes sharing the medium. The MAC sublayer in sensor networks and MANETs needs to be power-aware, self-organizing and support mobility and handoffs.

The network layer of such networks should perform routing so as to minimize power and the number of node hops in the route. In some cases, flooding/gossiping may be required to increase chances of the packets reaching the destination. Data aggregation/fusion may be used for data-centric routing [24] in the network layer. The network layer needs to allow for route maintenance and updates for fast changing network topology.

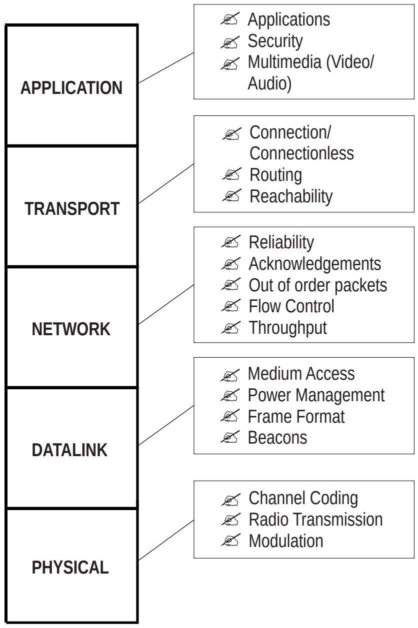

Fig. 2. Issues at each layer of the protocol stack

The transport layer is responsible for the end-to-end integrity of data in the network. The transport layer performs multiplexing, segmenting, blocking, concatenating, error detection and recovery, flow control and expedited data transfer. In the MANET environment, the mobility of the nodes will almost certainly cause packets to be delivered out of order and a significant delay in the acknowledgements is to be expected as a result. Retransmissions are very expensive in terms of the power requirements. Transport protocols for MANETs and sensor networks need to focus on the development of feedback mechanisms that enable the transport layer to recognize the dynamics of the network and adjust its retransmission timer, window size and perform congestion control with more information on the network.

The application layer needs support for location-based services, network management, task assignment, query and data dissemination for sensor networks and possible MANETs.

5. RELATED TECHNOLOGIES

In order to better understand UWB-based technologies, we look at some related technology standards. More information on these technologies can be found in Ref. 27.

5.1. Bluetooth

Bluetooth [14] is a short-range radio technology standard originally intended as a wireless cable replacement to connect portable computers, wireless devices, handsets and headsets. Bluetooth devices operate in the 2.4 GHz ISM band. Bluetooth uses the concept of a piconet which is a MANET with a master device controlling one or several slave devices. Bluetooth also allow scatternets wherein a slave device can be part of multiple piconets. Bluetooth has been designed to handle both voice and data traffic.

5.2. HIPERLAN/1 and HIPERLAN/2

HIPERLAN/1 and HIPERLAN/2 [16] are European wireless LAN (WLAN) standards developed by European Telecommunications Standards Institute (ETSI). HIPERLAN/1 is a wireless equivalent of Ethernet while HIPERLAN/2 has architecture based on wireless Asynchronous Transfer Mode (ATM). Both the standards use dedicated frequency spectrum at 5 GHz. HIPERLAN/1 provides a gross data rate of 23.5 Mb/s and net data rate of more than 18 Mb/s while HIPERLAN/2 provides gross data rates of 6/16/36/54 Mb/s and a maximum of 50 Mb/s net data rate. Both standards use 10/100/1000 mW of transmit power and have a maximum range of 50 m. Also, the standards provide isochronous and asynchronous services with support for QoS. However, they have different channel access and modulation schemes.

5.3. IEEE 802.11

This IEEE family of wireless Ethernet standards is primarily intended for indoor and in-building WLANs. There are several varities of this standard. The current available versions are the 802.11a, 802.11b and 802.11g (emerging draft standard) with other versions which are starting to show on the horizon [10]. The 802.11 standards support ad-hoc networking as well as connections using an access point (AP). The standard provides specifications of the PHY and the MAC layers. The MAC specified uses CSMA/CA for access and provides service discovery and scanning, link setup and tear down, data fragmentation, security, power management and roaming facilities. The 802.11a PHY is similar to the HIPERLAN/2 PHY. The PHY uses OFDM and operates in the 5 GHz UNII band. 802.11a supports data rates ranging from 6 to 54 Mbps. 802.11a currently offers much less potential for rf interference than other PHYs (e.g., 802.11b and 802.11g) that utilize the crowded 2.4 GHz ISM band. 802.11a can support multimedia applications in densely populated user environments. The 802.11b standard, proposed jointly by Harris and Lucent Technologies, extends the 802.11 Direct Sequence Spread Spectrum (DSSS) PHY to provide 5.5 and 11 Mb/s data rates.

5.4. IEEE 802.15.3

The emerging draft standard [11–13] defines MAC and PHY (2.4 GHz) layer specifications for a Wireless Personal Area Network (WPAN). The standard is based on the concept of a piconet which is a network confined to a 10 m personal operating space (POS) around a person or object. A WPAN consists of one or more collocated piconets. Each piconet is controlled by a piconet coordinator (PNC) and may consist of devices (DEVs). The 802.15.3 PHY is defined for 2.4 to 2.4835 GHz band and has two defined channel plans. It supports five different data rates (11 to 55 Mb/s). The base uncoded PHY rate is 22 Mb/s.

5.5. HomeRF

HomeRF [15] working group was formed to develop a standard for wireless data communication between personal computers and consumer electronics in a home environment. The HomeRF standard is technically solid, simple, secure, and is easy to use. HomeRF networks provide a range of up to 150 ft typically enough for home networking. HomeRF uses Shared Wireless Access Protocol (SWAP) to provide efficient delivery of voice and data traffic. SWAP uses a transmit power of up to 100 mW and a gross data rate of 2 Mb/s. It can support a maximum of 127 devices per network. A SWAP-based system can work as an ad-hoc network or as a managed network using a connection point.

6. CONCLUSION

In this paper, we presented an overview of UWB technology and its characteristics and advantages over conventional, continuous wave transmissions. We presented how UWB is well suited for several applications like sensor networks and MANETs. UWB technology has garnered a lot of interest among vendors who are looking at standardizing the use of the technology in various forums including IEEE.

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