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Ultra Wide Band (UWB) Ad-hoc Networks: Review and Trends

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Abstract: Short-range wireless systems have recently gained a lot of attention to provide seamless, multimedia communications around a user-centric concept in so called Wireless Personal Area Networks (WPAN). Ultra-Wide Band (UWB) technology presents itself as a good candidate for the Physical Layer (PHY) of WPAN, both for high and low data rate applications. Many ongoing developments of Ultra-Wide Band (UWB) system concentrate mainly on the physical layer, without significant considerations being given to the medium access techniques especially for targeted ad-hoc networking scenarios. Here, we further refine the framework, the network challenges, and defines a global network cost function, which takes into account both physical, and network layers parameters to derive general guidelines for ad-hoc networks based on UWB technology.

Key words: Wireless Personal Area Network, UWB, Ad-Hoc Network, Medium Access Control

INTRODUCTION

Ultra-Wide Band (UWB) has become a suitable candidate for indoor wireless communications; In particular, a multiuser access scheme for UWB because of the following benefits and characteristics [1, 2]: extremely low Power Spectral Density (PSD), spectrum reuse, robust performance under multipath conditions, multiuser communication, and high-resolution position location and tracking.

Currently deployed commercial wireless networks are built using either narrowband (e.g., cellular GSM) or wideband (e.g., 3G, 802.11) links. However, the demand for higher data rates at short-range distances has created a market for ultra-wideband links. UWB radios were designed as covert military applications, as a spread spectrum technology with large amount of bandwidth at extremely low powers, thus differentiating them from narrowband and wideband radios [3]. However, recent changes in U.S. federal regulations opened up UWB for commercial applications. Thus, there are currently intense research and development efforts underway, to design and standardize commercial UWB radios [4, 5]. For example, the UWB based IEEE 802.15.3.a standard [6] is expected to support 100 to 500 Mbps depending on the link distance. Further, UWB radios will be inexpensive and low power, making them ideal for ad-hoc wireless networks applications.

In ad hoc networking, the devices are interconnected via spontaneously created, disposable connections, without relying on a pre-existing infrastructure. These scenarios pose seriously challenging research tasks, since the same medium should be used by many mutually interfering WPANs under the stringent synchronization conditions imposed by the UWB.

UWB Physical Layer

UWB Transmission Principles: The Federal Communications Commission (FCC) defines UWB signals as having a fractional bandwidth of greater than 20%, or a UWB bandwidth 500 MHz at a low radiated power (–41.3 dBm/MHz) [7].

$$\text{Fractional bandwidth} = \frac{2(f_H - f_L)}{(H_H + f_L)} \qquad (1)$$

Where f_h and f_l are high and low frequency respectively. The UWB signals generation methods can be grouped in two major categories:

* Single-Band (SB) based: employing one single transmission frequency band, and
* Multi-Band (MB) based, employing two or more frequency bands, each, with at least 500 MHz bandwidth.

In the SB solution, the UWB signal is generated using very short, low duty-cycle, baseband electrical pulses with appropriate shape and duration. Due to the carrier-less characteristics (no sinusoidal carrier to raise the signal to a certain frequency band) these UWB systems are also referred to as carrier-free or Impulse Radio IR-UWB communication systems [8]. The MB UWB systems can be implemented carrier less (different pulse shapes/lengths are used according to the frequency band) or carrier based (multi-carrier like) [9, 10].

In order to convey the information symbols in UWB communications several approaches for the modulation techniques exist, mostly based on the classical base-band modulation types. Modulating the UWB pulse characteristics such as amplitude (PAM), time position (PPM), phase (PM), shape (PSM), or any combination of these, can be used. Another direct consequence of the large communication bandwidth is the possibility to accommodate many users, even in multipath environments.

The two most common channelization and Multiple Access (MA) techniques in IR-UWB are:

* Direct Sequence Spread Spectrum (DS-SS), similar to code division multiple access (CDMA) communication systems but using an UWB radio pulse as chip pulse shape and,
* Time Hopping Spread Spectrum (TH-SS), which uses UWB pulses pseudo-randomly shifted in time domain.

Fig. 1 shows the general transmission scheme for UWB signal (TH and DS), more details is available in [11]. In the case of PPM a pulse corresponding to a logical "zero" is transmitted by one pulse centered at time t_0, whereas a logical "one" is transmitted by pulse shifted by δ seconds (centered at $t_0 + \delta$). The last system is a pulse shaper filter with impulse response $w(t)$. The impulse response $w(t)$ must be such that general signal is a sequence of strictly non-overlapping pulses [12].

Time Hopping-Spread Spectrum for UWB: The key motivations to study TH-SS impulse radio are the ability to highly resolve multipath and the availability of the technology to implement and generate UWB signals with relatively low transceiver complexity [10]. For a multi-user (device) scenario, the format of the transmitted TH-SS IR-UWB signal, $s_{tx}^{(k)}$, corresponding to the *k*-th user (device) is given by:

$$s_{tx}^{(k)} = \sum_{j=-\infty}^{j=+\infty} w(t - j.T_f - c_j^{(k)}.T_c - \delta.b_{j/N_s}) \qquad (2)$$

Where T_f the pulse repetition time (typically a hundred or a thousand times the monocycle width), $c_j^{(k)}$ the time shift element of the time-hopping code word assigned to the *k*-th user; this element is chosen in the set $\{0,1,...,N_h - 1\}$, N_h is the number of time delay bins in a T_f, T_c the time delay bin, N_s is the number of impulses or impulse dedicated to the transmission of one bit *b*. the bit rate associated to one code word is then

$$R_b = 1/(N_s.T_f).$$

Fig. 2 shows an example of transmission by two users, each characterized by time hopping (TH) code word. Whereas the first user uses the TH code {1,3,0,2…}, the second uses the word {3,2,5,4…}. Each code word element corresponds to one of the possible N_h time shifts in

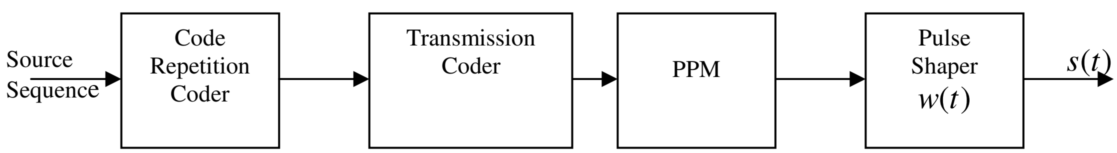

Fig.1: Transmission Block Diagram for UWB Signal (TH, DS)

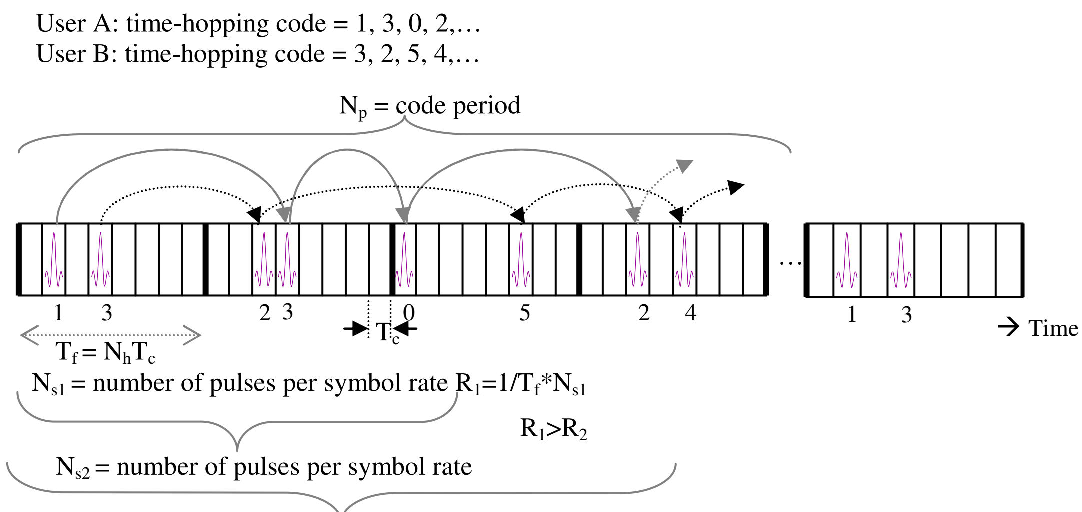

Fig. 2: UWB Multiple Access Scheme

the T_f period. In Fig. 3 we assumed the two users being synchronous with the T_f and to each other: while the first assumption can be easily satisfied, the second one is mor unrealistic. However, although the users are not synchronized with each other and the TH codes are chosen in a pseudo-random way, catastrophic collisions are compensated by transmitting several impulses for the same bit (N_s impulses per bit).

The UWB principal for the reception is based on correlator receiver with a correlation template signal $v(t) = w(t) - w(t+\delta)$, the decision is chosen based on the integration over N_s pulses:

$$\sum_{j=0}^{N_s-1} \int_{\tau_k + jT_f}^{\tau_k+(j+1)T_f} r(t).v(t-\tau_k - jT_f - c_j^{(k)}T_c)dt \qquad (3)$$

if the result is>0 then decide for a "0", otherwise if<0 then the decision is for a "1".

UWB PHY Capacity Promises: From Shannon's formula for the capacity in b/s of a single user in Additive White Gaussian Noise AWGN [13] we have the following for the capacity of the UWB system occupying bandwidth B, as a function of the signal to noise ratio SNR at a distance *d* between the transmitter and receiver:

$$C(d) = B\log_2(1+SNR(d)) \qquad (4)$$

The function $SNR(d)$ represents the effect of path losses on the transmitted signal. The FCC report and order R&O on UWB [14] allows for a UWB system bandwidth that extends from 3.1 – 10.6 GHz. The transmitted UWB signal is treated as having a constant power spectral density (PSD) over this band set by Part 15 limits. This UWB capacity is shown in Fig.ure 2 as a function of range. For comparison, the theoretical capacities in AWGN for some other unlicensed band WLAN systems are also shown. It can be seen that UWB systems offer their greatest promise for very high data rates when the ranges < 10 m, approximately. It should be noted that these capacity results are very simplistic, since only AWGN is considered [15, 16, 17].

UWB Multiple Access (MAC) Layer: The role of medium access techniques in wireless networks is to coordinate transmission access to common radio resources so that the interference among different transmissions is avoided or decreased and capacity (number of communication links with satisfied quality of service (QoS)) is maximized in the network. In the ad-hoc networking scenario, we have multiple collocated ad - hoc networks,

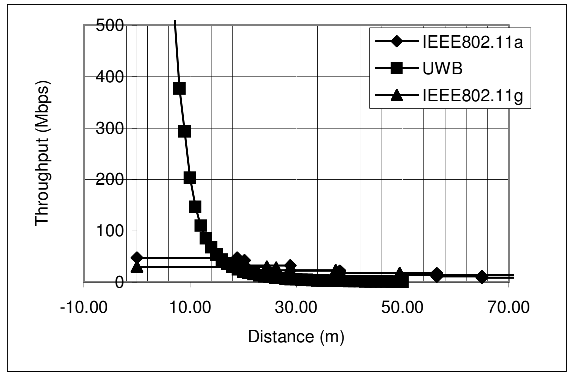

Fig. 3: Theoretical Capacity Comparison Between UWB and 802.11(a,g)

each of which is composed of personal devices of a user such as PDAs (personal digital assistant), laptop PCs, etc. Since ad-hoc technology uses license-free wireless links, the radio resources should be shared among the collocated and uncoordinated nodes. Thus, devices belonging to a single ad-hoc network should actually share the channel not only among themselves but also with the devices belonging to the neighboring, physically collocated networks. In the design of medium access techniques in such an ad-hoc context, we need to take account of two different control levels of interference. The first level of interference is *Intra*-ad hoc *Interference*, which is the interference among links located in single ad-hoc network. Employing traditional MAC protocols can control this level of interference. For instance, in Bluetooth based WPAN, polling scheme with Master/Slave operation, which is a contention-free MAC technique, has been adopted for this coordination [18]. Also, random-access techniques such as Carrier Sense Multiple Access (CSMA), or a combination of contention-free and random access techniques can be employed. The second level of interference is *Inter*-ad-hoc *Interference*, which is the interference among links located in different ad-hoc networks. Since it is difficult to coordinate the transmissions and completely avoid interference among devices in these uncoordinated nodes, the multiple collocated networks must share the resources in a sense to minimize the mutual interference, which can be achieved by adopting the transmission technologies that have the inherent immunity to the interference like SS technologies.

RESULTS AND DISCUSSION

Net Work Capacity: Recently, there has been significant interest in computing the capacity of ad-hoc networks [19, 20, 21, 22]. Consider ad-hoc wireless network, where *n* identical nodes on a unit area communicate over a wireless channel, with possible cooperation, and traffic to relay. Assume that each link operates at a fixed data rate, utilizing a finite bandwidth and large power (i.e., *SNR*). Under these assumptions, it was shown in [23], that the uniform throughput capacity per node decreases as a function of the number of nodes *n* as $\Theta(\frac{T}{\sqrt{n\log n}})$ where Θ is the standard order bounds. The essential reason for this capacity decrease is the requirement for all nodes to share the wireless channel locally. However under UWB communication model (large bandwidth, limited power), the uniform throughput capacity per node increases as $\tilde{\Theta}(n^{(\alpha-1)/2})$ [24], where $\tilde{\Theta}$ is the soft order bounds, and $\alpha \geq 1$ is the distance loss exponent. Future work includes designing optimal MAC and routing, which can achieve network capacity,(e.g. CDMA MAC and power-constrained routing) and designing a decentralized routing scheme to implement the power constrained routing.

A Position Based Routing Strategy: The fine time resolution available with UWB allows high precision ranging. With pulse duration shorter than one nanosecond, two nodes in the ad-hoc zone can determine their distance within a few inches. From the set precise pair-wise distances of ad-hoc nodes, a complete map of relative node positions can be reconstructed in a more precise way than with GPS, with no additional hardware requirements, thus enabling position aware functions in upper layers protocols, such as routing. Ranging information can be exploited in several ways in resource management. Examples are: a) Definition of distance related metrics for both MAC and higher layers, enabling the development of power-aware protocols e.g., [25]; b) evaluation of initial transmission power levels, required in distributed power control protocols [26]; c) introduction of distributed positioning protocols in order to build a relative network map starting from ranging measurements. The distance between nodes affect in the communication cost [27], which a communication cost is attached to each path, and the cost of a path is the sum of the costs related to the links it comprises. The cost of a link is expressed as:

$$c = \delta C_0 d^{\alpha} + C_1 R d^{\alpha} \qquad (5)$$

Where the parameter α is the channel propagation. Constant C_0 and C_1 are used to weight the signaling and transmission component.The first component of Eq. (5) takes into account the signaling cost for setting-up a new link. If two nodes already share an active link, $\delta = 0$ and there is no signaling cost. Otherwise $\delta = 1$. The second component takes into account the cost for transmitting data, and depends upon the requested data rate *R*. Both terms related to power consumption, and the distance between two nodes. Note that the evaluation of such a distance relies on the precise ranging capabilities offered by the UWB technique. The adoption of position-aware routing strategies significant improves the efficiency in power management for ad-hoc networks, by optimizing the path selection procedure. The above strategy however achieves a lower routing performance due to a higher percentage of path search failures. Future work will investigate if flexibility provided by complete UWB cost function [28] can enable a more accurate tuning of routing performance versus power efficiency, assuring optimal network performance in different network scenarios, and enabling QoS routing based on the selection of different routing metrics for different traffic classes.

Packet Routing in ad-hoc Networks and Medium Access Control: A key application for UWB devices is expected to be in the area of ad hoc and self-organized wireless networks based on multiuser communication and multihop routing capabilities [25]. In this area, subjects that offer significant research potential are (i) definition of MAC functions to support ad hoc network architectures (e.g. location-based routing), (ii) influence of cooperative routing and associated protocols on the network load, (iii) methods to determine location information (e.g. MAC frame that supports applications using data communication and ranging), and (iv) investigation of multiple access schemes for UWB radio devices such as code division multiple access (CDMA) in view of the digital communications for WLAN, ad-hoc networks and wireless access system. The future activities will be mainly dedicated to:

* The radio capacity-sharing model and relationship between traffic measurements and the interference/power.
* Define the detailed MAC protocol for radio resources control and the parameters that influences the protocol operations; in particular the interference level measured at physical layer will be expressed as a function of the active UWB communications in the ad-hoc MAC zone and of other transmission s at radio frequency [29].
* Analyze the interactions of MAC with IP upper layer supporting also procedures aiming at guaranteeing the QoS.
* Analyze the interactions between a routing in ad-hoc MAC zone (eventually in a multi-hop modality) and the routing in the IP-QoS zone.

CONCLUSION

The peculiar characteristics of the UWB radio channel offer new solutions and opportunities for resource management and networking was discussed. The ultimate benefits that UWB could bring to ad hoc networking from increase network data rate, mitigate multiuser interference MUI, increased capacity, and the ability to couple location tracking with (high-performance) data transmission, which improves the efficiency in power management for ad-hoc networks was presented.

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