A Survey on Ultra Wide Band Medium Access Control Schemes

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Abstract

Ultra wideband (UWB) technology based primarily on the impulse radio paradigm has a huge potential for revolutionizing the world of digital communications especially wireless communications. UWB provides the integrated capabilities of data communications, advanced radar and precision tracking, location, imperceptibility and low power operation. It is therefore ideally suited for the development of robust and rapid wireless networks in complex and hostile environments. The distinct physical layer properties of the UWB technology warrants efficient design of medium access control (MAC) protocols. This paper introduces the unique UWB physical characteristics compared to the existing wireless technologies and discusses current research on MAC protocols for UWB. This report surveys most of the MAC protocols proposed so far for UWB, and may instigate further activities on this important and evolving technology.

1. Introduction

Ultra WideBand (UWB) communication systems are usually classified as any communication system whose instantaneous bandwidth is many times greater than the minimum bandwidth required to deliver information. The excess bandwidth is a defining characteristic of UWB.

The first wireless transmission via UWB emissions was sent by Marconi from the Isle of Wight to Cornwall on the British Mainland in 1901 using Marconi Spark Gap Emitter [4]. The UWB signal was created by the random conductance of a spark. Then in the late 1970s and early 80s, Fullerton demonstrated the practicality of modern low power impulse radio techniques using time coded time modulated ultra wide band approach.

The Federal Communications Commission (FCC) is the radio frequency (RF) regulatory body in the United States. It controls spectrum division and licensing. It had earlier consigned UWB to experimental work only, commercial use was not allowed. In 2002, the FCC changed the rules to allow UWB system operation in a broad range of frequencies. In 2003, the first FCC-certified commercial system was installed [17], and in April 2003 the first FCC-compliant commercial UWB chipsets were announced by Time Domain Corporation.

There are several methods of generating and radiating UWB signals. The most popular waveform used is the TM-UWB which consists of ultra short monocycle wavelets with tightly controlled pulse to pulse intervals. The pulse to pulse interval is varied on a pulse to pulse basis depending on the information signal and the channel code. Although there are other methods for generating the UWB signal, the impulse based waveform is the most popular one. Hence, we focus on the impulse waveform UWB signal in this paper.

The most important design requirements for UWB based networks are:

- providing a method to allow a user to decode a particular data stream
- allowing all the users to efficiently share the media spectrum range
- techniques to build the system with sufficient performance or cost advantage over existing approaches to justify the effort and investment.

In this paper we address the second issue, i.e., media access by multiple users, popularly known as the medium access control (MAC) layer. The most important functions of the MAC layer for a wireless network include controlling channel access, maintaining quality of service, and providing security. MAC protocols proposed for narrowband wireless systems like CSMA/CA, IEEE 802.11, IEEE 802.15.3 and their variations are unsuitable for the UWB system because of the following reasons:

- Clear channel assessment is necessary for CSMA/CA method of channel access. In case of UWB, clear channel assessment by energy detection is difficult with UWB-PHY because of very low power emissions. The energy is spread in a large frequency bandwidth causing low energy at the receiver. Furthermore, UWB signals using PPM (pulse position modulation) is practically carrierless. Hence carrier sensing cannot be done.
- Voice and video, which are the targeted applications for UWB technology, cannot tolerate large transmission delays and jitter.
- High channel acquisition time because of long synchronization between transmitter and receiver causes CSMA/CA to deliver poor channel utilization for short packet sizes. Hence IEEE 802.11-based protocols are very ineffective for the UWB technology, especially in ad hoc mode when the signaling overhead to attain synchronization could be too high. In the wireless environment, packet sizes should not be too large. Because of the lossy nature of wireless media there is a tendency of higher bit error rate for larger packets.[3]
- Although MAC for Bluetooth or wireless personal area networks (IEEE 802.15.3) could be applied with little modification to MAC for UWB, it will fail to take advantage of UWB properties like localization, highly secure low power operation and large bandwidth.

The unique nature of UWB technology, therefore, requires a MAC with additional features not observed in the existing MAC protocols for narrowband wireless communications. The requirement for strict synchronization between transmitter and receiver, precision timing and location that can be used to synchronize the received packets at different receivers of a multicast network (multiple audio speakers/video displays) and low power operation necessitates a MAC optimized to take advantage of these properties.

The rest of the paper is organized as follows: Section 2 details some of the distinctive feature of UWB and advantages and disadvantages thereof. Section 3 lists some of the current and future applications of UWB technology. Section 4 discusses the design principles of medium access protocols for UWB currently proposed. We summarize the paper in Section 5.

2. UWB Characteristics

UWB is a carrierless technology since there is no intermediate frequency stage. Data is transmitted in the form of digital pulses of electromagnetic energy. UWB signals are characterized by very wide bandwidths and ultra short pulse width. Various advantages and disadvantages resulting from these three main features are discussed in this section[1].

2.1 Large bandwidth

Digital impulse radio, also called ultra wide band radio is a generic term used to describe radio systems having very large bandwidths. The definition of UWB transmission given by FCC is a signal whose fractional bandwidth is greater than $1/4^{th}$ the center frequency or a bandwidth greater than 500MHz [5].

Advantages:

a) *High data rate communications* [11]: The channel is the RF spectrum within which information is transferred. Shannon's capacity limit equation shows capacity increasing as a function of bandwidth (BW) faster than as a function of signal to noise ratio (SNR).

$C = BW \times \log_2(1+ SNR)$,

where, C is the channel capacity in bits/sec; BW is the channel bandwidth (Hz); and SNR is the signal to noise ratio.

$SNR = P/BW \times N$,

where, P is the received signal power and N denotes the Noise Power Spectral Density (watts/Hz).

Shannon's equation shows that increasing channel capacity requires linear increases in bandwidth while similar capacity increases would require exponential increases in power. Therefore UWB technology is capable of transmitting high data rates using very low power.

b) *Multiple access communications*: Due to large bandwidth, an UWB based radio multiple access communication system can accommodate many users. Multiple access with UWB signals is better accomplished using code division multiplexing in conjunction with pulse-position modulation, as compared to frequency division multiplexing because code correlation is a useful method for isolating multipaths.

c) *Ground and wall penetration and geolocation*: Narrowband communication signals must use higher carrier frequencies in order to implement a wider bandwidth. As the frequencies of these signals increase, the propagation losses they experience becomes greater. UWB signals achieve high data rates with lower center frequencies. Hence UWB signals have the potential for greater penetration of obstacles such as walls. This is primarily because of the frequency dependence of the penetration of materials by RF signals.

d) *Low power stealthy communications*: UWB provides low probability of detection and low probability of jamming as a result of using low energy per frequency band and use of precisely timed patterns. Hence, UWB technology is very suitable for high security applications such as military communications.

Disadvantages:

a) *Potential interference to and from existing systems*: FCC has defined power masks (emission masks) to give extra protection from a UWB device at frequencies containing the existing 2.4 GHz ISM band that is used by current wireless local area networks such as IEEE 802.11 and wireless personal area networks like Bluetooth. Most of the time the resulting UWB signal is below the noise floor of many receivers due to the wide distribution of signal energy in bandwidth.

The amount of interference at an UWB receiver due to a narrow band transmitter depends on the antennas used and their orientation. Use of direct sequence or time hopping spread spectrum modulation makes it possible to mask out a powerful narrowband interfere without significantly impacting the UWB receiver's ability to process the desired signal. Minimum mean square error multi user detection schemes with the ability to process multipath data are capable of rejecting strong narrowband interference.

2.2 Carrierless Signal

Conventional narrow and wide band systems use radio-frequency carrier to move the signal in the frequency domain from baseband to actual carrier frequency. A UWB implementation can, instead directly modulate an impulse that spans several GHz of bandwidth. Hence, UWB technology is also referred to as carrier-free technology. Data is transmitted in the form of digital pulses of electromagnetic energy. UWB signal composition is quite complex. For example, the description in [10] can be summarized as follows: a 31.25µs timeslot carries one full duplex bit. However the bit is transmitted multiple times within the timeslot. 1023 doublets spaced 10ns apart compose one timeslot. Doublets are pairs of RF pulses sent as different frequencies. The first pulse of a doublet is an indication of a data pulse to come. The second pulse is a binary 0 or 1, depending on its delay after the first pulse (e.g. a slightly retarded pulse could represent 0 and a slightly advanced pulse could represent 1). 29 timeslots form one 29 bit Epoch, lasting 1 ms. One packet contains 32 epochs, 32 packets form an Era and requires 1024 ms.

Advantages:

a) *Hardware simplicity and small low cost hardware*: Traditional carrier based technologies modulate and demodulate complex analog carrier waveforms. In contrast UWB systems are made all digital with minimal RF or microwave electronics. Also home UWB wireless devices do not need transmitting power amplifier. This is an advantage over narrowband architectures that require amplifiers with significant power back-off to support high order modulation waveforms for high data rates. UWB transmitters can directly modulate a baseband signal eliminating components and reducing requirements on tuned circuitry. In particular UWB technology has the following advantages:

- The transmitter needs no D/A converter
- The A/D converter need not be of high resolution, since the information is not embedded in signal phase
- Digital shaping filter is not used
- No equalizer is required to correct carrier phase distortion
- With low order modulation, the transmission is reliable enough and may not need forward error correction and the corresponding decoder at the receiver
- Fewer RF components imply small, mature CMOS technology can be used.

b) *Low Power Operation*: Another reason for UWB devices to consume less power is that UWB transmits short impulses constantly instead of transmitting modulated waves continuously like most narrowband systems do. UWB chipsets do not require RF (Radio Frequency) to IF(Intermediate frequency) conversion, local oscillators, mixers and other filters hence transmitter power requirements are low.

c) *Supports smart sensor network applications*: The potential for low-power, simple hardware using carrier-less transmission makes UWB technology an attractive alternative for distributed sensor networks.

Disadvantages:

a) *Not supporting super resolution beam forming*: A beam is formed by phasing different antennas so that the combined signal's carrier is coherent when sent to or received from, a particular direction. The theory of beam forming and super-resolution beam forming is based on phase relationships among sinusoidal waveforms and does not apply directly to pulse based UWB systems.

b) *Complex signal processing required*: For narrowband systems that use carrier frequency, frequency-division multiplexing is very straightforward and the development of a narrowband device need only consider the band of frequencies directly affecting itself and minimizing interference to out-of-band systems by emission control techniques like filtering and wave shaping. For carrierless transmission and reception, every narrowband signal in the vicinity is a potential interferer and also every other carrierless system. So any carrierless system has to rely on relatively complex and sophisticated signal processing techniques to recover data from the noisy environment.

2.3 Ultra Short Pulse Width

UWB signal is transmitted as low power radio signals in ultra short electrical pulses, in the picosecond range, across all frequencies.

Advantages:

a) *Multipath components of UWB signals can be resolved directly*: Multipath interference happens when wireless communication systems experience echoes at certain frequencies from secondary signals that bounce from buildings or other obstacles just after the original signal is received. UWB signals use short pulses so pulses belonging to different multipath reflections tend not to overlap in time (their direct resolvability). As a result, the pulses do not interfere with each other and individual paths tend not to fade, unlike continuous wave signals whose multipath components always overlap and incur fading.

b) *Provides for diversity gain from combining multipath components*: Since multipath reflections of UWB signals are resolvable, there is a potential for obtaining diversity gain by combining them.

c) *Low power combined communications and localization*: Localization of radio signals indoors is difficult because of the presence of shadowing and multipath reflections from walls and objects. The fine time resolution required by UWB signals makes them ideal for high resolution positioning applications.

d) *Multipath persistence property*: Since the various reflected pulses tend not to overlap in time, mutual interference of multipaths is low. Hence multipaths arrive at the receiver with less attenuation than for narrowband signals. This is referred to as multipath persistence. Multipath persistence has the advantage of low fade margins which implies lower power requirements for transmitters.

e) *Multipath persistence property supports NLOS (Non line of sight) communications such as indoors and aboard ships*: Usually, localization of a radio signal's source is best done under line of sight (LOS) conditions, and multipath components interfere. Hence, it is difficult to use conventional RFID techniques aboard ships because radio transmissions aboard ships and those situations in which metal containers are used, tend to have many reflections. However UWB signals propagate well aboard ships, into corners and round objects because UWB signals and multipaths do not fade fast and also because of their low frequencies they propagate through objects better.

Disadvantages:

a) *Produces a large number of multipath components*: A large number of multipaths exist because of the reflective environment, and they are observable in case of a UWB signal because of the picosecond precision of the UWB signal, the multipaths do not overlap in time and therefore, don't interfere or cancel out.

b) *Pulse coding of signals require relatively long synchronization times*: Since picosecond precision pulses are used in UWB, the time for a transmitter and receiver to achieve bit synchronization can be as high as a few milliseconds. Hence the channel acquisition time is very high which can significantly affect performance especially for intermittent communications.

3. UWB Applications

The motivation for discussing UWB technology comes from its applications and the advantages it offers over other narrowband technologies. Some of the current and future applications of UWB technology are[5][9]:

- *Applications in Wireless Communication Systems*:

1. High bandwidth wireless network for homes and offices.
2. Roadside Information stations that can be deployed where the messages may contain weather reports, road conditions, construction information and emergency assistance communication.
3. Automotive in-car services like real time video for directions and passenger entertainment, or download driving directions from PDA for use by onboard navigation system
4. Short range voice, data and video applications
5. Military communications on board helicopters and aircrafts which would otherwise have too many interfering multipath components.

- *Applications for Radar and Sensing*

6. Ground penetrating radar
7. Vehicular Radars used for collision avoidance/detection and sensing road conditions
8. Through wall imaging used for rescue, security and medical applications
9. Identification tags
10. Radar security fence
11. Multi-sensor robots for reconnaissance

- *Applications in Precision Location Tracking*

12. In container inventory systems :RFID
13. Aiding GPS for localization.
14. Localization in search and rescue efforts

Some implementations of these applications are[18]:

1. **VETAS** : Vehicular Electronic Tagging and Alert System initiated by the US Department of Transportation to provide a means of keeping repeatedly convicted drivers off the road. The concept was to tag the vehicle with a device that relays a picture of the driver and the vehicle to a roadside sensor in a police vehicle.
2. **WICS** : UWB Wireless Intercom Communications System for US Navy aircraft. The transceiver provides multi channel, full duplex 32kbs digital voice across a a range of ~100m. UWB was the chosen technology because of its ability to operate in multi path (created by RF reflections inside the aircraft), its non–interfering and low probability of intercept signature.
3. **MANET** : Development of highly mobile, multi-node, ad-hoc wireless communications network funded by the Office of Naval Research. The system is designed to provide a connectionless, multi-hop, packet switching solution for survivable communications in a high link failure environment.

4. **Firefighter (PLT) Radio**[4]: TM-UWB radio is used as a precise, self-referencing, 3-d position location tracking and voice communications systems for firefighters inside and outside of buildings. TM-UWB radios are able to take advantage of multi-path, thus making them ideal for this application as optical and GPS based systems will not work in smoke filled buildings.

4. Medium Access Protocols

Having discussed the physical attributes and the applications of the technology we can now delve into the functionality and principles that guide the MAC layer design for the UWB system. The MAC protocol governs the control of multiple user channel access in a secure manner with quality of service guarantees. This functionality has to be attained with minimal overhead in terms of power, latency and bandwidth. As discussed in Section 1, existing wireless protocols are either not applicable or not optimized for the UWB communication system. Hence a MAC designed specifically for UWB attributes is required. These attributes are: high channel acquisition time as a result of long synchronization, ranging abilities, low power operation and carrierless pulse position modulation. In this section, we review various MAC protocols proposed for UWB technology.

4.1 WPAN-Based MAC

Most applications for UWB are short range Wireless Personal Area Networks (WPAN) or medium range WLAN. This is mainly because of the FCC restriction on the range of UWB signals. Hence many companies and organizations including the IEEE are focusing on the enhancement of the existing narrowband WPAN MAC or the 802.15.3 [22] standard to make it a better fit for UWB technology. Another reason for this effort is to allow for interoperability between existing narrowband WPAN technologies and UWB based WPAN.

One such approach has been undertaken by the European funded Ultra Wideband concepts for Ad-hoc networks (UCAN) project group funded by Information Society Technologies [6][14]. UCAN follows the single band model and implements UWB as Impulse Radio as opposed to Direct Sequence Spread Spectrum and have implemented their transmitter and receiver based on this concept.

UCAN has considered different topologies corresponding to different applications. These can be categorized in three simplified models:

- Short range communication, e.g. linking domestic appliances to local PC and other such WPAN applications.
- Hot spot coverage and network backbone interconnection e.g. PDAs communicating using UWB technology
- Clusters of ad-hoc networks, comprising of a large number of nodes covering large areas using message hopping.

For the MAC architecture UCAN focuses mainly on WPAN and medium (WLAN) range applications for reasons already cited above. The UCAN MAC is a modification of the IEEE

802.15.3 standard [22]. It adds ranging and relaying features. It also provides for both asynchronous and isochronous data transfers with QoS. It uses time-hopping code division as against frequency division multiplexing for coexistence of multiple WPANs.

4.1.1 MAC Superframe

The MAC protocol is centrally coordinated using a PicoNet coordinator (PNC) [6] which is dynamically chosen when the piconet is created. Piconets[2] are single hop networks consisting of one master and up to seven slaves. This architecture can be extended to form scatternets by sharing slaves. The PNC synchronizes devices and allocates resources. If the PNC disappears another station can take on its role as all devices have the same hardware configuration. Note that the topology can be formed in an ad-hoc manner and communications are in peer to peer mode even though the MAC protocol is centralized.

Time division multiple access (TDMA) was chosen for channel access in intra-piconet communications and Time Hopping – Code Division Multiple Access (TH-CDMA) for inter-piconet communications.

UCAN piconet is based on the superframe which is a fixed length of 10ms. This is divided into three zones: Beacon, Random access and Variable length channel time allocation slots. UCAN MAC does not use the contention access period within the superframe since clear channel assessment is hard because of low power emissions. Four levels of service priority are defined. Three kinds of frames are used: data, control, and command frames. The command frames also include measurement frames used to support UWB ranging functionality and relaying command frames. The superframe structure is as shown in Figure 1.

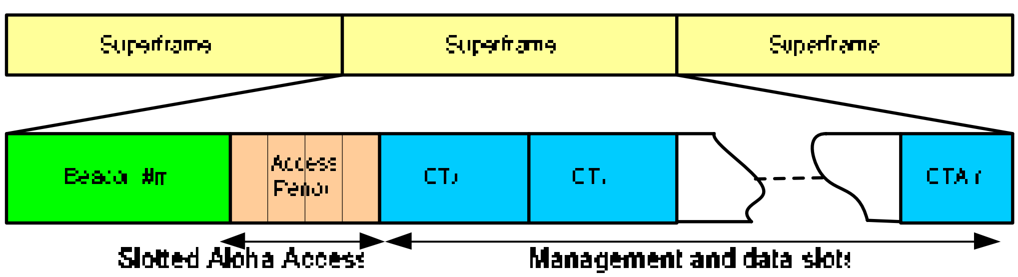

Figure.1: The superframe structure

PNC dynamically allocates resources when a device wants to relay messages, making resource allocation efficient. Priority is given to relaying streams over new streams in order to prevent problems like half-way blocking when devices that require two hops are allocated resources only for the first hop. The relaying cost function is based on the distance between the devices and is expressed as: $C(x, z) = [d(x, y)]^2 + [d(y, z)]^2$.

4.1.2 MAC Routing

a) UCAN defines a routing metric based on the following parameters:

- Power Efficiency
- Synchronization overhead
- Multi-user interference
- End-End delay
- Route Quality
- Traffic balancing

The routing strategy chooses the path with the minimal cost as computed by the routing metric. The routing metric is therefore a link additive cost function of the form[7]:

C(x,y) = C(power) + C(setup) + C(interference) + C(quality) + C(delay),

where C(x,y) is the cost of the direct link from x to y

The cost of a communication path is the sum of the cost of its links

C(path) = ∑ C(x,y), (x,y)€path

The cost of the link varies in time and the parameters defined by the originating request. e.g. C(power) may be defined as :

C(power) = C_1. R (x, y). d^{α} (x, y)

Where R = requested rate
d = distance between the two terminals
α = positive number based on propagation characteristics (usually between 2 and 4)

b) The routing algorithm uses the positioning information based on UWB ranging capability. However it also provides for position independent routing for scenarios when such information may not be available like initial start up phase. An on-demand routing protocol similar to the Location Aided Routing (LAR) protocol [21] is chosen since reactive algorithms are cited to be of better use than proactive algorithms, especially as reactive protocols adapt better to fast topology changes in small ad-hoc networks. The routing protocol utilizes UWB ranging and positioning information to define a forwarding zone based on source and expected destination position and the original LAR was adapted to allow intermediate nodes to forward more than one packet related to the same request. To make the routing power efficient, an optimized cone-shaped request zone is selected which guarantees minimal number of route request packets sent during a route discovery procedure.

The main advantage of the UCAN approach is that it uses the localization properties inherent to UWB for ranging, distance measurement and routing. Synchronization is relatively easy because.of the piconet approach and it could be made to interoperate with other IEEE WPAN technologies like Bluetooth since it is based on the same guidelines. On the other hand, the piconet approach works only for WPANs, hence its applicability is limited and non-scalable to large networks. No justification has been provided for the choice of the location aware routing algorithm used.

4.2 A Complementary Code-CDMA-Based MAC Protocol

Jiang et al [19] present a complementary code-code division multiple access (CC-CDMA based) MAC protocol for UWB WPAN system which is also inspired from the IEEE 802.15.3 standard and uses the piconet architecture. CDMA technology is used to provide orthogonal channels and phase shifts are used to identify multiple users. The characteristics of this MAC protocol are:

- higher bandwidth utilization
- lower requirement on system timing
- energy efficiency obtained by minimizing collisions and retransmissions, idle listening, overhearing and control overhead.
- higher spreading gain
- higher throughput and lower average packet delay as compared to the CSMA/CA.

Multiple access in this MAC is implemented in the following manner. Different users are identified by different phase offsets of the complementary code (CC). This approach implements a simpler timing control mechanism than identifying multiple users based on the different delays.

The piconet coordinator (PNC) assigns a spreading code to every device that associates to it. The devices use this to transmit channel time requirements and other messages to the piconet. A special spreading code is assigned for unassociated devices to send their association requests to the PNC. The MAC protocol timing in a piconet is structured in superframes, similar to that in IEEE 802.15.3. A superframe is divided into three zones, viz., the beacon frame, the CC-CDMA based contention free access period and the channel time allocation period. These are described as follows:

Beacon frame: This is transmitted by the Piconet coordinator to synchronize devices and broadcast information about the piconet characteristics and the resource attribution.
CC-CDMA based contention free access period: This is the collision free period based on CC-CDMA, which is achieved by using access request packets that are orthogonal and hence non interfering at the receiver. Acknowledgement for this phase is done in the beacon of the next superframe. All devices in a piconet use a single spreading code and are distinguished by the relative phase shift of the code.
Channel Time Allocation based contention free period: During this period the devices in a piconet are allocated CTA slots by the PNC to transmit data frames.

The advantages of this approach are the simpler timing mechanism and receiver circuitry design as compared to delay based on user differentiation and high processing gains. The probability of successful channel access is 1 and hence is more efficient in terms of throughput and latency as compared to CSMA/CA. This approach has a few shortcomings: The high spreading factor makes it less efficient and more complex. It does not utilize UWB characteristics for precise tracking and immunity to jamming that would be desirable in a more generic UWB network architecture.

4.3 Time Hopping Based Distributed MAC Protocol

WHYLESS is a project sponsored by the European Union to study the potential of UWB for the development of an Open Mobile Access Network [8][14]. This section discusses the basic principles used for Medium Access Control in this project. UWB waveform is implemented as impulse radio using pulse position modulation. Multiple accesses to the radio resource by several users is established by using Time Hopping codes chosen in a pseudo random way. Collisions are avoided and compensated for by transmitting several impulses for the same bit. The multiple access control protocol used has the following key characteristics:

- It allows for the development of a wireless network composed of large number of radio nodes
- It is flexible in terms of resource utilization and topology definition
- It allows for ease of scalability, re-configurability and self-organization
- It can co-exist with other radio systems within the defined constraints of power, spectrum occupation etc.
- It allows for support of quality of service (QoS) in the internet.

A distributed MAC mechanism is considered although this introduces complexity in the radio resource control. The network is composed of TermiNodes (TN). These elements are small personal devices that act as both node and terminal. The network is modeled as a hierarchical structure of the following domains:

- *UWB domain*: wireless area where UWB is used for communication between TNs.
- *Multi-hop domain*: Within the UWB domain, the area where multi-hop connectivity is used to obtain an end-to-end wireless communication path.
- *Multiple access control domain*: where control for access to radio resource is done, typically done by each TN. Therefore this domain exists for each TN centered on the TN but also includes the area where transmission of TN has an impact on the transmission/reception of other TNs.

4.3.1 MAC implementation

a) *Support for "best effort" IP traffic and some classes of traffic with QoS guarantees*: MAC splits the radio resource in two parts

- *Dynamic Bandwidth (DB)*: This is dynamically (re)configurable by the MAC on a per packet duration on the basis of two parameters: the amount of DB packets waiting for a transmission and the interference level in the MAC domain. This resource supports the best effort traffic in the IP layer.
- *Reserved Bandwidth (RB)*: This bandwidth is negotiated with the network layer and once allocated varies only according to an explicit QoS request from the network layer per session (i.e. once allocated it remains valid for the entire session). It maps the QoS classes of the IP layer. It has the added overhead of reserving this bandwidth, even though it may not be used.

b) *Logical Channels*:

- *Physical Common Control Channels*: These channels are accessed by TNs in a MAC domain using a time hopping code and are mainly used for set up procedures.
- *Physical Dedicated Control Channels*: These channels are accessed by TNs and used to support dedicated control information relevant for data communications.
- *Physical Dedicated Traffic Channel*: These channels are accessed by TNs using time hopping code for data communication.

c) *Architectural Model*: The following functional entities can be distinguished:

- Radio Resource Control (RRC):
  - The RRC is responsible for reserving RB flows and handling the configuration/reconfiguration of radio capacity.
  - The RRC calculates available capacity in the system to perform RB, DB control
  - The RRC optimizes multiple access by varying parameters like: family of time hopping codes, number of time hopping codes assigned to a user, number of transmitted pulses per bit, distance between two pulses, period of time hopping code, impulse shape and duration, time shift associated with transmission of 0 or 1 and the transmission rate.
- MAC/RLC: It is composed of the following functional entities:
  - *RLC entities*: These entities implement fragmentation and de-fragmentation and ARQ procedures. They also monitor retransmission buffers and sends the occupancy status to RLC Control
  - *MAC-traffic server*: This server, serves the RB, DB flows with packets based on priority and with the capacity value assigned by the capacity manager.
  - *MAC-signaling server*: This server buffers signaling packets, implements ARQ mechanism for them and forwards them to the component of the physical layer depending upon the signaling channel to be used.
- Physical Layer: Performs UWB transmission and reception

4.3.2 MAC Protocol

The following steps are adopted in the MAC scheme:

Step 1: The transmitting TN (TN_A) interrogates active TNs in its MAC domain to derive appropriate margins for the power level and transmission parameters selection.

Step 2: TN_A communicates to the destination TN_B, the selected transmission parameters and time hopping codes to be used in the communication

Step 3: Destination TN_B verifies if the declared power level associated to the incoming communication is compatible with the interference conditions in its MAC domain.

If yes, Goto Step 4 else, send an alarm to all active TNs in its (TN_B) MAC domain to ask for possible reduction on their power levels.

Step 4: TN_B answers the request to start a communication with TN_A. If they agree on the transmission parameters, goto Step 5

Else, Setup fails or goto Step 1 aiming to obtain wider margins for power levels and parameters selection

Step 5: The setup ends positively and the two TNs communicate.

This procedure will be repeated for new setups or for reconfiguration of the parameters.

The key advantage of this approach is that it is a distributed protocol and thus can be used in different topological configurations. The MAC protocol selects optimal power level and transmission parameters, and hence is power efficient. Thus, the network can have a higher capacity. On the other hand, this issue makes it complex to implement and has a high network overhead in terms of synchronization of nodes, etc. It does not take full advantage of the UWB technology like localization and low probability of detection and jamming.

4.4 MAC Protocols for Multimedia Support in UWB Networks

The characteristics of MAC protocols used for supporting multimedia applications include support for high data rates and QoS in terms of guaranteed bandwidth. Network capacity and hence channel capacity is an important factor in multimedia applications. Channel capacity for UWB depends on the transmission power and is limited by the receiver side signal to noise ratio (SNR) threshold that is required for successful transmission. The SNR ratio threshold in turn depends on the path gain between a transmitter and receiver.

Boudec, et al. in [13] propose a centralized and distributed MAC protocols for UWB that leverage the high bit rate capability of the technology to provide multimedia support for such networks while satisfying the SNR constraint and adapting transmission power according to the interference level and the required bit rate [13]. The protocols support two traffic classes, viz., best effort and QoS. When channel capacity drops QoS traffic is given priority while the bit rates may drop for best effort traffic.

The UWB network considered for the MAC is a homogenous network where every node is within a hop's distance of every other node. Every node knows the path gain values of all other nodes in the network. This can be computed by using the transmission and receiver power or the distance between two nodes obtained from ranging algorithms. A separate control channel apart from data channel is used for signaling purposes.

4.4.1 Distributed MAC protocol

In the protocol described in [13] every node performs admission control and resource allocation on a per link basis depending on control information received from other nodes. All nodes in the network periodically transmit their identity, path gain and interference margin. This information is cached by other nodes in the status table. The status table stores (a) interference margins of every node, (b) path gain values and (c) new link requests differentiated as QoS request or BE request.

The protocol functions in two modes: cooperative and non-cooperative. In non cooperative mode, a node will not change the bit rate or transmission power during transmission whereas in cooperative mode it will distinguish between QoS and BE traffic and lower the bit rate for BE traffic to accommodate QoS flows.

The protocol functions as follows:

1. A QoS request comes in for link (i,j). If either i or j are actively transmitting/receiving then the request is rejected.
2. Based on the interference margins of all the nodes the power required for transmission is calculated, if this is valid (>0) then the available bit rate is calculated based the power.
3. If the available rate is higher than the required rate then the request is accepted and bit rates of all BE links are updated.

If the request is for BE service, then current BE throughput is compared with the reallocated (recalculation of bit rates for all BE traffic including the new link) throughput. If the reallocated throughput is higher than the BE throughput then the request is accepted.

4.4.2 Centralized MAC Protocol

In the centralized scheme, the protocol uses a piconet structure like IEEE 802.15.3 standard, where the piconet coordinator monitors traffic requests and performs resource allocation in terms of bit rate and transmission power based on the physical layer measurements. The control and data channels are divided into superframes. In the control channel, the superframe is divided into uplink and downlink periods. The uplink period is further divided into minislots for every node to transmit its physical layer measurements and traffic requests. The PNC transmits resource allocation information in the downlink period using which the nodes can schedule transmission on the data channel. The time slot scheduling algorithm for the data channel is modeled as a K-coloring problem solved in polynomial complexity. The resource allocation algorithm is represented as an optimization problem, wherein the total power of all links is to be minimized (to minimize interference and increase usage) subject to the SNR constraint. QoS links are assigned a higher priority and hence are scheduled before BE links.

The key benefit of this approach is that it uses both distributed and centralized protocols that take advantage of UWB's high bit rate to provide multimedia support. It takes into account the SNR constraint and uses exclusion, rate adaptation and power control to achieve an optimal design. The design is flexible in terms of allowing dynamic reconfiguration of transmission parameters to minimize interference and improve channel capacity. It uses a cross layer approach (physical <-> MAC) to optimize channel usage. Also the assumption of every node being in one hop distance of every other node is limiting and does not scale.

4.5 A Proactive and Adaptive UWB Medium Access Control Protocol

Ultra Wideband MAC (U-MAC) [15] is a proactively adaptive protocol that addresses the following issues:

- Joint assignment and optimization of transmit rates and transmission power in a proactive manner using hello messages without incurring heavy control overhead
- Fair access to the medium among nodes regardless of the distance
- Quality of service
- Better network efficiency as compared to a reactive protocol.
- The protocol can work in centralized (when an AP is present to connect to) as well as decentralized (ad hoc mode) manner.

Every node sends out periodic hello messages that contain their state information. The periodicity of the messages is adaptive based on the node stability. If the node is stable the periodicity in increases until it reaches a specified maximum value. If the node is unstable (mobile, physically unreliable and high number of state changes) than based on the level of instability (e.g. relative velocity) the periodicity is decreased until it reaches a specified minimum value. If a change occurs in an otherwise stable node, it will trigger the transmission of hello messages advertising this new state to all neighbor nodes. Based on the state information received by a node from its neighbors, the node can compute the interference levels and hence deduce the power and rate that it can permit for a new link or adjust the power and rate of existing links for best effort traffic. Addition of a new link can cause state changes in a number of nodes. This may result in a burst of hello messages. The hello messages on state changes are transmitted after a random backoff period to avoid the burst and hence prevent further interference. Nodes use hello messages to determine the distance of the neighbor from which it received the message. It can then compute path loss to that neighbor based on the current distance information. The hello messages include the following information

- Mean time between failures, (this is a reliability attribute of the node.)
- Maximum sustainable interference (MSI),
- Aggregate power level of all active links,
- The fraction of MSI attributed to this traffic class (DB or RB)

Each node stores a neighbor list that is updated with every new connection or loss of an existing connection based on the hello messages.

The protocol supports two classes of service similar to those described in Section 4.2. One is the reserved bandwidth (RB) that may be used for multimedia traffic and the other is dynamic bandwidth (DB) that mirrors best effort traffic. A fraction of MSI is attributed to RB traffic and the rest to DB traffic. Every time a new DB link is added the rate of all the current DB links are adjusted so that total interference does not exceed the specified value. However in the RB the rate is fixed, hence no dynamic adjustment is made.

U-MAC also provides a mechanism to adjust the radius around a receiver within which all nodes get fair access to the receiver. Time hopping codes with pulse position modulation are used to support multi user media access. One code is reserved for control channel and another for the hello messages. If a node hears hello messages from an AP , it switches to centralized mode.

Figure 3 shows the control messages exchanged on addition of a link. Sender, S sends a Request To Send (RTS) message containing the rate and power values to the receiver R. On receiving an RTS, node R and all other neighbors of S check whether the requested link is admissible based on the interference and the SNR (Signal to Noise Ratio) values. If admissible, R notifies S with a Clear to Send (CTS) control message. Other neighbors of S do not send any replies if the link parameters are acceptable. If the receiver node R or any other neighbor of S does not agree with the parameters of the new link, then that node notifies *S* with a Not Clear to Send (NCTS). NCTS implies that the sender should reduce either the transmit power or rate or both. After *S* collects all the replies, it declares the duration and parameters of the new link (which may have changed according to neighbor replies) in a Reserve message indicating the rate, power and duration of the link. The receiver synchronized with the TH code of the sender on receiving the reserve message. All node that hear the reserve message update their interference levels, if the update is significant than the node transmits a hello message after the link setup is completed.

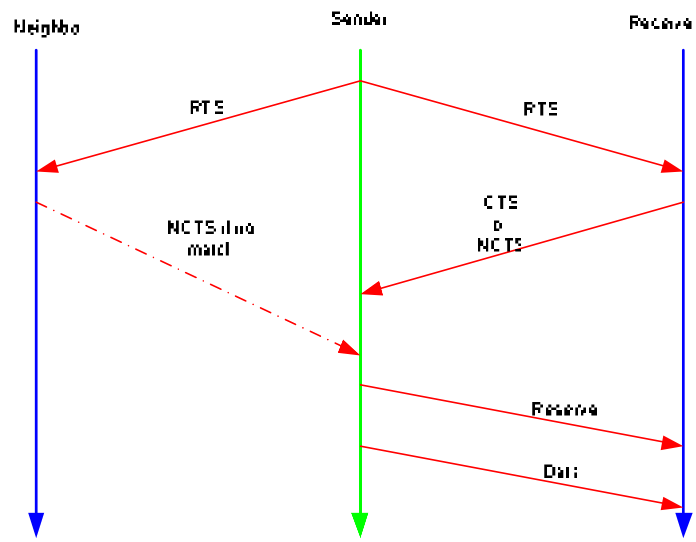

Figure 3

This protocol jointly optimizes transmission power and rates. It uses the ranging capability of UWB to compute path loss based on distances to determine the optimal transmit power.The periodicity of the hello messages are adaptive, hence control overhead adapts to network stability. This protocol addresses QoS and fairness issues. According to the simulations, this proactive protocol performs better than reactive approaches in terms of link set up latency, network throughput and adaptability to high network loads. However, the simulations and design is only for a single hop case, although the authors mention that the scheme can be generalized to multi-hop. Again, the protocol does not address security and how to use UWB to facilitate it.

4.6 MAC Protocol for UWB technology used in very low Power Mobile Ad-hoc Networks

In contrast to U-MAC, where the power is varied depending on the interference the signal to noise ratio, the authors in [16][12] propose a distributed protocol for very low power (1µW) ultra-wideband mobile ad hoc networks based on dynamic channel coding. The protocol combines the physical and the MAC layer. The key idea in [16] is to optimize rate by allowing interfering sources to transmit simultaneously if they are outside the 'exclusion' region of a destination by dynamically adapting the channel codes depending on the interference. The interference within the exclusion region is dealt with using a 'private' MAC protocol that involves nodes trying to transmit to the same destination simultaneously. The achievable bit rate for the specified power using this technique is in the range of 1-18Mbps. The exclusion region is a circular area around the destination within which temporal exclusion between two sources results in a better throughput than resolving the interference caused by simultaneous transmission.

Pulse position modulation is used to represent the UWB signal. The sources transmit at full power and adapt the channel code to allow a common destination to distinguish between interfering signals. The channel code selected also changes the bit rate of the transmission. Hence, the bit rate may be varied based on the interference by varying the channel code. This protocol therefore optimizes the UWB MAC by allowing transmissions at maximum power, permitting simultaneous interfering transmissions outside the exclusion region and using temporal exclusion with the exclusion region.

Signal transmission: Time is divided into chips of short duration in the order of nano seconds (T_c). The chips are organized into frames. The length of each frame is equal to the pulse repetition period. One source will transmit one pulse per frame in a chip the index of which is determined by a random number generator. The maximum achievable capacity is if multiple sources are transmitting pulses in independent chips. The frame size or PRP must be large to ensure low power operation. The authors assume a PRP of 280. If the received energy level is higher than the intended receive power, the destination declares an erasure thus triggering retransmission. The probability of erasure is computed as 0.18% which causes a rate reduction that is much lower than temporal exclusion protocols. The rate reduction grows less linearly than the number of interfering sources, since interferences can overlap causing a single erasure to mitigate the effect of multiple interferences.

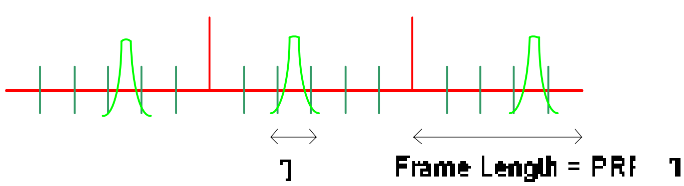

Figure 4: Signal transmission and the frame length

MAC Protocol:

The MAC protocol is geared to achieve maximum flow control within the constraint of very low power emissions. This is achieved by the following approaches:

- Applying an interference mitigation procedure at the demodulator: A channel encoder is used before the modulator that selects an encoding rate and encodes an incoming block of data blocks. The modulator then converts this PPM form to be transmitted over the physical medium. Rate Compatible Punctured Convolutional Codes (RCPC) are used to provide variable encoding in order to achieve data rates within a specified range. A source transmits one pulse per frame and a time hopping sequence is used to determine which chip in each frame to transmit the pulse in. Note that increasing the PRP decreases the bit rate but also decreases multiple user interference. Interference mitigation has to be performed within the exclusion region, which is done by executing an erasure at the symbol level on a chip if the signal strength detected is higher than a specified value.

- Using dynamic channel coding and incremental redundancy: Channel coding is constantly adapted to the highest achievable rate code that permits accurate decoding of the packet at the destination. A safety margin is used to mitigate retransmissions in case channel conditions deteriorate. The protocol proceeds as follows:
    - The Source encodes the packet content and CRC at the lowest rate code
    - It then uses RCPC on the encoded packet to obtain a higher rate and transmits the packet
    - On reception, the Destination decodes the data, checks the CRC and sends an ACK to the source if successful otherwise sends a NACK.
    - On reception of a NACK, the source sends incremental bits until the packet is decoded or until it has no extra information to transmit in which case the Source retransmits the packet after a backoff period.

- Private MAC within the exclusion region: A private MAC is required to resolve contention between multiple sources and a single destination. This is done by using a combination of receiver based and invitation dependent selection of time hopping sequences. The protocol proceeds as follows:
    - A node (destination : D1) listens to its own THS
    - If a source (S1) wants to communicate with the destination it sends a transmission request on the source's THS using the channel code for the lowest rate.
    - D1 sends a reply using a THS private to S1 and D1 and the channel code obtained from the channel code assignment procedure.
    - If S1 receives a reply, it indicates that D1 is idle and S1 starts transmission of the data packet using the THS private to S1 and D1
    - S1 adjusts its code based on feedback from D1. In the absence of feedback, S1 performs a retransmission after a backoff period.
    - After a transmission both source and destination nodes issue an idle signal on their THS respectively in order to inform other nodes that they are idle.
    - If D1 is busy then S1 waits to hear the idle signal from D1 and then waits for another random backoff time before retransmitting.

The main benefits of this approach are that the MAC adapts to the varying channel and therefore, supports medium mobility levels and ad-hoc mode. The design is simple as no power control is used. No separate control channel is used as is done in U-MAC. The protocol takes advantage of the interference resistance property of UWB to reduce the exclusion region to a minimum increasing the channel capacity. However, this design does not discuss routing, flow control or multiple service classes. This protocol may never achieve the high rates of the other protocols because of the requirement for large PRPs. The authors assume resynchronization for every packet which implies a high overhead. It would be better to have synchronization for a session or resynchronization in case of channel loss. Finally, since broadcast THS (time hopping sequence) is different, hence a receiver has to synchronize with both broadcast THS and data THS which could cause some latency issues.

4.7 A Multiband MAC Protocol for Impulse-based UWB Ad Hoc Networks

The authors in [20] present a case for multi-band UWB MAC for use in ad hoc networks. Different bands are used for control and data transmission. Multiple access is achieved by using multiple bands- one band per source destination pair. The available frequency bandwidth is divided into data bands and a request band each of bandwidth 500MHz. Two communicating nodes use the control channel (Request band) to facilitate a rendevouz in another band used for data exchange.

The first band is designated as the request band though any band can be chosen as the request band. Time hopping similar to the one described in [16] is used in the control channel to share a single frequency band among multiple users.

Time is divided into frames requiring synchronization of communicating nodes. There are two kinds of frames, superframes and availability frames.
-*Superframe*: Superframes are used for data and control communication. Superframes are divided into sequence frames, each of which consists of chip-times.

-*Availability frames:* The availability frame is used to indicate the status (busy or idle) of the multiple bands, in the next superframe. An availability frame is present between the last sequence frame of the superframe and the first sequence frame of the superframe. Availability frames are used to reduce collisions during *data transmissions* in superframes. Nodes using a data band can signal their continued use of the band during the next superframe in the availability frame. The availability frame is divided into *availability slots* corresponding to the number of data bands. Communicating nodes “saturate” the availability slot that corresponds to the data band that they intend using in the next superframe. The sender saturates the first half of the slot and the receiver the second half. Consecutive transmission of pulses during the availability frame enables the nodes to sense the pulses.

Control Flow
The MAC protocol is implemented as a state diagram as shown in figure 5.

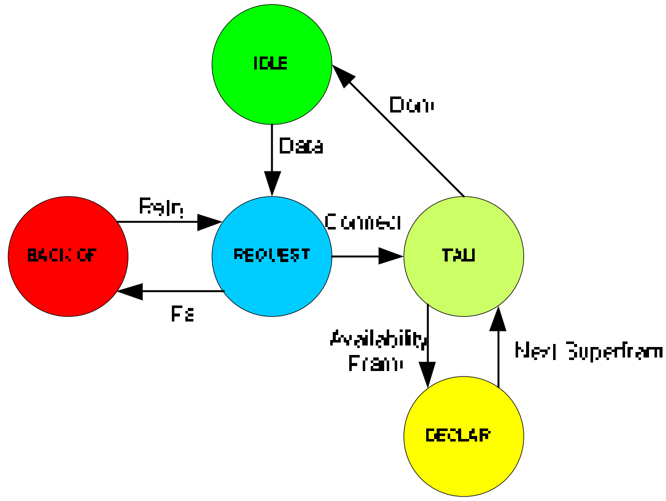

Figure 5: State diagram of the MAC protocol

The states are described as follows:
IDLE State : Initially a node is in IDLE state.

REQUEST State: In this state node attempts to initiate a request to a receiver. The sender sends a *REQ packet* in the Req-Band as per the THS of the receiver. The REQ packet contains the band chosen by the sender for data exchange. This band is chosen depending on the 'free' bands indicated by the availability frame, its own history of band usage and the bands have a history of being in use as learnt from the availability frames. The sender then waits for a response from the receiver on the indicated data band. If the receiver receives the REQ packet correctly it switches to the specified data band in the REQ packet, and sends a *RACK (Request Acknowledgment)* packet to the sender. On reception of a RACK the sender switches to TALK state.
If the request fails, the sender enters the BACK-OFF state and tries again at a later time.

BACK-OFF state: While in the back off state the node switches to the Req-Band to enable receptions on its THS while its backoff counter is running. If the node receives a REQ packet it freezes its backoff timer temporarily and switches to the band specified in the REQ packet, to receive data from the sender of the REQ packet. On either completion of the reception or detection of a collision, the node switches back to the Req-Band and resumes the countdown of its back-off timer.

TALK State: Data communication between the sender and receiver takes place in this state.

DECLARE State: While transmitting data in the TALK state, the sender periodically transitions to the DECLARE state and announces in the availability frame, that the specific data band is in use. Upon the completion of the data transfer, the node returns to the IDLE state.

In order to avoid collisions a pair of nodes that switches to a new band for communication are required to wait for a duration of nanoseconds before commencing data transfer and receivers are required to send short *occupancy* indication messages in the data band with a periodicity of nanoseconds.

The main advantages of this approach is that the use of control channel limits the contention on the shared channel. The communication on the data band can be contiguous and does not require time hopping sequences, hence is more efficient. Probability of collisions in transmission of large data packets is reduced leading to higher throughput and lower latencies than single band approach. The protocol avoids high synchronization time and transmission of large synchronization sequence is avoided. The authors however do not provide any details of the node synchronization scheme used. There is no mention of the MAC implementing any QoS.

Apart from the UCAN and U-MAC protocols none of the other protocols discussed take advantage of the localization properties of UWB and none of them use the imperceptibility property on the UWB technology. The CC-CDMA MAC, the MAC for UWB very low Power MANs and the Multiband MAC protocol do not discuss or implement multiple service classes. Also while some of the MAC protocols described are power aware or use the low power feature of UWB technology others do not.

5. Conclusion

UWB systems are mostly based on the impulse Radio (IR) technology that uses extremely short pulses (e.g. picosecond duration) giving rise to a wide spectral occupation in the frequency domain (bandwidth from near DC to a few GHz). UWB offers the unique property of integrated data communications and localization information at high security and low power requirements with a good level of immunity to interference like multipath fading.

UWB technology can be used for a wide range of applications, the prominent ones of which are ground-penetrating radars, imaging systems, vehicular radars, wireless offices and homes, RFID in ships or metal containers, smart sensor networks and rescue operations like firefighters.

FCC regulations limit the frequency of UWB, thereby also limiting its range. Hence most efforts on building a MAC Layer protocols for UWB systems have focused on modifying the existing WPAN standard 802.15.3 for UWB-PHY which would also enable interoperability. However it still remains to be seen how well MAC would perform against one which is designed specifically and optimally for UWB technology.

Some more issues which need more delving into are optimal location aware routing protocol for a UWB network as well as the security policy to be implemented at the MAC level, given that it can be used in conjunction with sensors because of its localization, low power and high security properties. Interoperability with other wireless technologies like Bluetooth and 802.11 will play a large role in UWB gaining acceptance in data communications.

Most of the existing MAC protocols for UWB leverage one or two properties of UWB to cater to a specific application. However the full potential of UWB can be realized only if all the aspects of the technology are considered while designing a MAC. It would be best to make these as tunable parameters so that they can be turned off or set to particular values for different applications.

UWB is an upcoming technology whose potential at the physical level has been long realized but requires an optimal standardized and flexible MAC designed to take advantage of its unique properties before it can be a fully functional technology put into commercial use.

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