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(UWB)^2: Uncoordinated, Wireless, Baseborn Medium Access for UWB Communication Networks

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Abstract. A MAC protocol for Ultra Wide Band (UWB) radio networks named (UWB)^2 is proposed. The algorithm exploits typical features of impulse radio such as large processing gain, and is conceived in conjunction with a synchronization strategy which foresees the presence of a synchronization sequence in each transmitted packet. (UWB)^2 adopts a pure Aloha approach; Performance analysis of the synchronization tracking mechanism showed in fact that under the preliminary simplistic hypothesis of an AWGN channel, and for a sufficient number of pulses in the synchronization sequence, a fairly high probability of successful synchronization can be achieved, even in the presence of several users and Multi User Interference (MUI). The multiple access scheme is based on the combination of a common control channel provided by a common Time Hopping (TH) code with dedicated data channels associated to transmitter specific TH codes.

Results obtained by simulation indicate that (UWB)^2 can be successfully applied when the number of users spans from a few tens to about one hundred, for data rates ranging from a few thousands to a few hundreds of bits per second. Network throughput was above 99.8% in all considered simulation settings. Such achievement confirms that (UWB)^2 is a suitable and straightforward solution for large networks of terminals using impulse radio for transmission at low bit rates.

Keywords: ultra wide band, synchronization, Medium Access Control

1. Introduction

Ultra Wide Band (UWB) emissions cover large portions of the frequency spectrum, and must in principle coexist with other Hertzian waveforms propagating over the air interface. The principle of coexistence imposes upper bounds on UWB power emissions so as to limit interference on existing narrowband services. In April 2002 by releasing UWB radio emission masks the Federal Communications Commission (FCC) in the USA [9] opened the way for the concept of coexistence with traditional and protected radio services. The emission masks issued by the FCC regarding indoor UWB systems strongly limit however operation to a -10 dB bandwidth lying between 3.1 and 10.6 GHz, and set very stringent limits on out of band emissions. The FCC emission masks serve at present as a reference for UWB system design within and outside the USA. As far as Europe is concerned for example the European Radio Organization (ERO) issued in July 2003 a tentative definition of UWB emission masks which very closely follow the FCC settings [24].

A severe power emission constraint is genuinely suited to transmissions at either high bit rates over short ranges or low bit rates over medium-to-long ranges.

The high bit rate/short range case includes Wireless Personal Area Networks (WPANs) for multimedia traffic, cable replacement applications (such as wireless USB), and wearable devices (e.g. wireless Hi-Fi headphones). The low bit rate/medium-to-long range case applies to long-range sensor networks (e.g. indoor/outdoor distributed surveillance systems), non-real-time data applications (e.g. e-mail and instant messaging), and in general all data transfers compatible with a transmission rate in the order of 1 Mb/s over several tens of meters.

In either of the above frameworks the design of an UWB network must include the definition of a Medium Access Control (MAC) module. The MAC should be specifically conceived for the UWB radio physical layer, and as such foresee and eventually optimize strategies for power sharing and management. Currently published MAC proposals for UWB are the IEEE 802.15.3 standard [14], and the protocols by Cuomo et al. [6], and Kolenchery et al. [16].

The IEEE 802.15.3 standard [14] defines a MAC protocol for high bit rate applications (11–55 Mb/s) in WPANs (10–20 m). The standard was originally developed based on a traditional, narrowband (15 MHz on-air bandwidth) physical layer in the 2.4 GHz unlicensed band. The recent increased interest for UWB rushed the adoption of this standard also in the case of an UWB physical layer.

Medium access in 802.15.3 is based on the organization of the devices in piconets. Each piconet is controlled by a PicoNet Coordinator (PNC). In order to exchange data with other devices, a device must register at the PNC of a piconet by means of an association procedure. In order to initiate the association procedure the device must have previously achieved time synchronization with the PNC. The PNC grants channel access to successfully associated devices on a TDMA basis. The PNC role in a piconet can be played by different devices at different times, and a specific PNC handover procedure is defined in order to transfer the PNC role from one device to the other within the piconet. The decision about moving the

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PNC role is demanded to the current PNC and is based on the comparison of PNC capabilities across devices.

The PNC controls channel access by assigning time slots to requesting devices. Time slots, named Channel Time Allocations (CTA), are encapsulated into frames. The duration of a frame as well as frame structure is controlled by the PNC. The frame structure is in general organized as follows:

- A Beacon Period: this portion of time is reserved to the PNC, which broadcasts information for piconet management, such as device associations or disassociations, scheduling of CTAs, and modifications of frame duration.
- A Contention Access Period (CAP) during which random access to the channel is granted to all devices within the transmission range of the PNC. A Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) protocol is used by devices to access the channel in the CAP. Non-associated but synchronized devices may use the CAP to send an association requests to the PNC. Associated devices use the CAP to either send small amounts of data or request to the PNC for CTAs to be used in subsequent frames.
- Contention Free Period (CFP): this portion of the frame is organized into CTAs, used by associated devices to send data packets to other devices in the piconet. Scheduling of CTAs is broadcasted by the PNC during the Beacon Period. The CFP may also include special CTAs, called Management CTAs, which can be used by synchronized devices to start an association procedure.

Durations of the different periods can be varied by the PNC according to piconet size and traffic scenario. The PNC is also in charge of controlling the interference level in its piconet. Intra-piconet interference is mitigated by the TDMA structure, while inter-piconet interference may occur if independent piconets are located in the same area. The PNC monitors the channel with eventually the help of other associated devices, and switches to a different channel whenever the experienced interference level is excessive.

The Cuomo et al. protocol [6] proposes a distributed admission control function based on the evaluation of the interference generated by each potential new link over active links. Based on the approach originally proposed in [1] for CDMA networks, the admissibility of a new link is determined by predicting its effect on the Signal to Noise Ratio (SNR) characterizing each active link.

The evaluation of the potential effect of a new link on the network is demanded to the transmitter requesting a new link, which in turn relies on information provided by terminals involved into active links. The protocol foresees therefore the activation of a procedure involving message exchange aimed at providing the new transmitter with the information needed for applying the admission rule. Two different admission rules are proposed in [6] for best effort and Quality of Service (QoS) traffic, respectively.

In the case of best effort, the aim of the protocol is to maximize network throughput by only allowing new links which lead to an overall throughput increase. The effect of the new link is thus evaluated by comparing the increase of overall throughput guaranteed by its activation with the decrease caused by the reduction of rates on active links as required to keep the target SNRs in the presence of increased interference. When the overall balance is positive, the new link is activated. A hand-shake procedure provides the requesting terminal with the information required for evaluating the admission condition.

In the case of QoS traffic, existing links must maintain a minimum bit rate value. A new link is thus admitted only if its effect can be tolerated by all active links, i.e. only if the increased interference still allows each link to achieve the target bit rate with the requested SNR. A handshake procedure provides the requesting transmitter with the SNR margins of active receivers, i.e. the amount of additional interference each link can tolerate. The procedure is further refined in [7] and [5], where the authors propose a periodic broadcasting of margins in place of the on-demand transmission adopted in [6].

The MAC protocol proposed by Kolenchery et al. [16] aims at minimizing transmitted power for covertness purposes. The proposed protocol supports multiple full-duplex links at the MAC level, and is based on the idea of maintaining the physical connection between UWB devices also during inactive periods in between successive data bursts. The re-establishment of a link at the physical layer does not require thus to transmit signalling packets. By reducing the number of control packets reduced power, and consequently increased covertness, is obtained. With reference to multiple access, logical links are established by using a distributed handshake at the MAC layer consisting of RTS (Request to Send)/CTS (Clear To Send) signalling messages. After a link is established, user data packets are transmitted using link-specific Time Hopping (TH) codes. These packets are typically transmitted at high bit rates. The protocol also includes power control. Unlike conventional packet radio systems, however, power control information is not piggy-backed on data packets but rather packaged into smaller MAC data units and transmitted during inactive periods at low bit rates and low power levels.

Neither the 802.15.3 standard, nor the Cuomo protocol are specifically tailored for UWB systems. In the case of 802.15.3, the MAC structure is totally independent of the underlying UWB physical layer; The adoption of a TDMA access scheme does not exploit for example the possibility of using TH codes within a piconet. In the Cuomo protocol although multiple access is based on TH codes the admission control function relies however on a Multi User Interference (MUI) model which is valid in general for CDMA networks, but not specific to the impulse nature of UWB transmissions.

The MAC scheme proposed by Kolenchery [16] is more focused in taking into account features of impulse radio. Both UWB-specific signal acquisition and packet synchronization problems are taken into account. Reference is made to the high bit-rate case, and within this framework a dynamic and distributed power control scheme is required in order to maintain a desired level of Signal to Interference Ratio (SIR) at each receiver.

All of the above MAC proposals are suited to applications referring to the high bit-rate/short distance scenarios. A recent standard release of the IEEE 802.15.4 for Low Rate WPANs [15] has however increased attention and interest towards low bit rate applications. To this regard, the first commercial UWB precision asset location system named PAL-650 operating at an average rate of 70 bits/s over a couple of hundred meters in outdoor links was recently presented [10].

The goal of this work is therefore twofold:

1. Define a MAC which incorporates UWB peculiarities and in particular large processing gain together with high precision in ranging;
2. Define a MAC for low bit-rate UWB networks.

For this purpose MAC functions which can benefit from specific UWB features must be identified. We therefore first derive an analytical model for MUI based on pulse collision probability. Starting from the definition of pulse detection error probability we derive Bit Error Rate (BER) and Packet Error Rate (PER) as a function of UWB parameters. This model is used for selecting a synchronization strategy capable of guaranteeing a high probability of successful synchronization at the physical layer. We show that, thanks to outstanding UWB features such as very high processing gains, a high synchronization probability can be obtained also in the case of asynchronous networks in which several users access the system without any, neither centralized, nor distributed, coordination. This framework forms the basis for the definition of a MAC protocol named $(\text{UWB})^2$ in which users send packets in a totally uncoordinated manner. The baseborn Aloha hypothesis was first suggested in [17] and is further investigated in the present paper.

Further we introduce in the protocol a specific procedure to perform ranging and collect distances among nodes in the network. Although the protocol is capable of operating without this feature, strategies for resource management and allocation can be optimized thanks to the additional distance information.

The paper is organized as follows. Section 2 presents a short overview of UWB radio, provides the analytical model for MUI characterization, and introduces the synchronization scheme. The $(\text{UWB})^2$ protocol is described in Section 3. Section 4 contains the experimental data obtained by simulation of the $(\text{UWB})^2$ protocol, while conclusions and future work are included in Section 5.

2. Physical layer foundations for the $(\text{UWB})^2$ protocol

In this section key features of UWB radio are briefly reviewed, in order to support the assumptions made in the definition of the $(\text{UWB})^2$ protocol. The interested reader will find an exhaustive description of UWB radio characteristics in [3].

2.1. Ultra wide band radio characteristics

UWB radio in its impulse radio version is based on the emission of very short pulses which are modulated in time (Pulse Position Modulation, PPM) or amplitude (Pulse Amplitude Modulation, PAM) by the information bits [2].

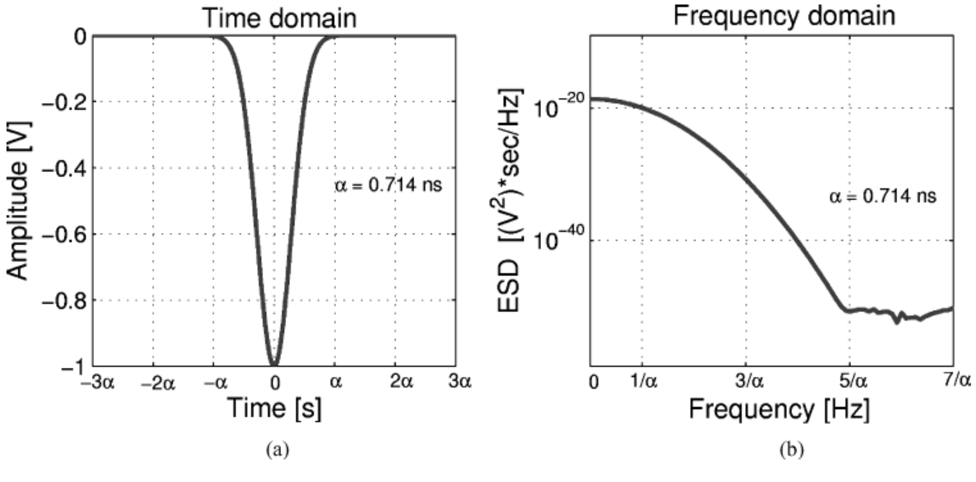
The pulse at the receiver is generally assumed to be the second derivative of the Gaussian pulse [26], expressed by:

$$\omega_{\text{rec}}(t) = [1 - 4\pi(t/\alpha)^2] \exp[-2\pi(t/\alpha)^2] \qquad (1)$$

where α is a shape parameter. Figure 1 displays the typical shape of the pulse and of its Energy Spectral Density (ESD) at the receiver, with $\alpha = 0.2877$ ns.

Pulse duration is usually selected to be a fraction of nanoseconds, and therefore pulses spread their energy over a frequency bandwidth of several GHz. UWB signals must then in principle coexist with narrowband radio systems. As a consequence stringent limits and bounds over emitted power must be verified at all times.

In the case of PPM the UWB signal is quasi-periodic due to the rather small PPM shift value which is usually adopted. In



(a) (b)

Figure 1. Pulse shape of the second-derivative Gaussian pulse. Time waveform and corresponding Energy Spectral Density are shown in figure 1(a) and (b), respectively.

order to mitigate energy peaks at multiples of the average pulse repetition frequency, time intervals between UWB pulses must be randomized. The use of TH codes has the beneficial effect of smoothing the UWB spectrum since it adds up to the PPM shift an additional pulse time shift which is variable according to the code. In particular, the average pulse repetition period T_F is split into N_H sub periods called chips of duration T_C. Each element of the code specifies the chip interval in which the pulse must fall and be transmitted.

In TH-UWB systems, as we will further consider in this paper, Multiple Access is obtained by assigning different TH codes to different users [23]. TH codes must have low cross correlation characteristics to ensure low MUI in the presence of several accessing terminals.

In order to increase robustness in the transmission each bit is usually encoded into N_S pulses. The data rate of a single user is thus:

$$R = \frac{1}{N_S \cdot T_F} = \frac{1}{N_S \cdot N_H \cdot T_C} \tag{2}$$

Coding each bit with N_S pulses corresponds in fact to introducing redundancy for protecting transmissions against pulse losses due to either collisions with pulses emitted by other users (MUI), or narrowband interference generated by other radio services.

In summary, when Multiple Access is achieved by using TH codes, the composed signal corresponding to N_U users can be expressed as follows

$$s_{\text{rec}}(t) = \sum_{k=1}^{N_U} \sum_{j=-\infty}^{\infty} \omega_{rec}\left(t - jT_F - c_j^{(k)} T_C - \varepsilon \cdot a_j^{(k)}\right) \tag{3}$$

where $c_j^{(k)} T_C$ is the shift on pulse j provided by the TH code of user k.

2.2. Multi user interference modelling

In a TH-UWB system, the TH principle allows simultaneous access to the network by different users. Pulses belonging to different transmissions will eventually collide. The time occupied by one single UWB pulse indicated by T_P is defined here as the time interval typically centered on the main lobe in which most of the energy of the pulse at the receiver is concentrated. Typical values for T_P lie between 70 psecs and 20 nsecs depending upon transmitted pulse shape and channel behaviour. Under the reasonable hypothesis for asynchronous networks that the pulse inter-arrival process follows a Poisson distribution, the probability that one or more pulses collide with the useful pulse when P_U packets are transmitted over the air interface by N_U active users can be expressed as:

$$Prob_{\text{PulseCollision}} = 1 - e^{(-2 \cdot (P_U - 1) \cdot \frac{T_P}{T_F})} \tag{4}$$

P_U depends upon N_U, packet length L, data rate R, and packet generation rate G. Its average instantaneous value is:

$$P_U = \frac{N_U \cdot L \cdot G}{R} \tag{5}$$

Assuming that a pulse collision causes a random decision at the receiver the pulse error probability can be expressed as:

$$\text{Prob}_{\text{PulseError}} = 0.5 \cdot \text{Prob}_{\text{PulseCollision}} \tag{6}$$

Considering that each bit is encoded into N_S pulses we assume an error on the bit when more than $N_S/2$ pulse errors occur. This corresponds to assuming a hard receiver detection [19]. Bit error probability is thus expressed by:

$$\text{Prob}_{\text{BitError}} = \sum_{i=\lceil \frac{N_S}{2} \rceil}^{N_S} \binom{N_S}{i} \cdot \text{Prob}_{\text{PulseError}}^{i} \cdot (1 - \text{Prob}_{\text{PulseError}})^{N_S - i} \tag{7}$$

Consider for example an UWB network in which $N_U = 100$ active users generate packets at a rate $G = 10^3$ packets/s using a packet length $L = 1000$ bits. The data rate R is set to 10 Mbits/s. Every station transmits therefore at an average rate of 1 Mbit/s. In average $P_U = 10$ packets are present in the air interface at a given time. For example if $T_P = 80$ psecs and $N_S = 11$ then $\text{Prob}_{\text{BitError}}$ is $2.57 \cdot 10^{-4}$.

Here, we assume that a packet is corrupted if at least one bit error occurs within the packet.

The average probability to transmit a packet successfully $\text{Prob}_{\text{Succ}}$ is thus given by:

$$\text{Prob}_{\text{Succ}} = (1 - \text{Prob}_{\text{BitError}})^L \tag{8}$$

$\text{Prob}_{\text{Succ}}$ depends upon the number of packets P_U and data rate R as displayed in figure 2 (full lines). Figure 2 also shows data obtained by simulation (dashed lines) for the specific case of a rate $R = 10$ Mbits/sec. The simulator used to derive the above experimental data implements the whole transmitter-receiver chain at the physical layer. The effect of thermal noise was neglected in these simulations. Both analytically derived and simulated values were obtained with the following settings: $L = 50$ bits, $T_P = 80$ psecs, and $N_S = 11$. Note that the simulated values follow closely the analytical prediction, and provide therefore good support to the analytical model. Also note that for low data rates in particular the probability of packet error is extremely low ($< 10^{-4}$) for a number of packets in the air interface as large as about 50.

2.3. Synchronization

Synchronization in UWB networks is a delicate task due to the very short pulse duration and low duty cycle. The receiver must be able to detect UWB signals superimposed with noise and interference.

We propose here a synchronization scheme which is based on the presence of a fixed synchronization trailer. Each data packet contains the synchronization trailer which is a priori known by all network participants, and allows a receiver to detect incoming packets. The synchronization trailer consists of a fixed number of pulses M, and is located at the beginning of each packet as shown in figure 3. We assume that synchronization can be maintained for the whole duration of a packet, and must be re-established for each single packet. This

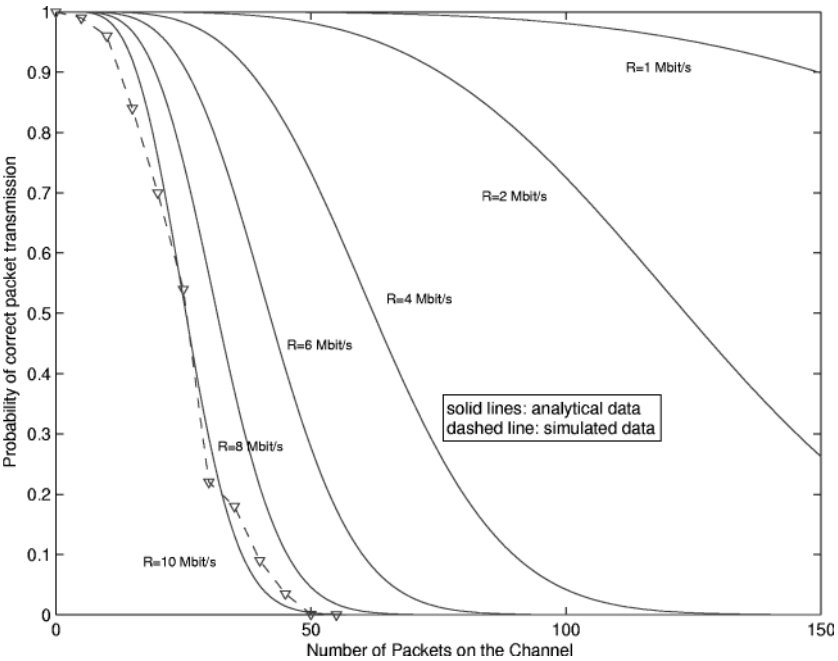


Figure 2. Probability of successful packet transmission as a function of the number of packets on the channel. Different solid lines correspond to different data rates from 1 to 10 Mbit/s. The dashed line shows simulation results in the specific case of $R = 10$ Mbit/s.

Figure 3. General packet structure.

assumption takes into account the impulse nature of UWB, and the presence of clock drifts between two stations. Within a packet the synchronization procedure is such to keep tracking of synchronization, while in between two packets, when the tracking is not active, synchronization might be lost after a time-lag which depends upon time drifts of local oscillators. For quartz-crystal oscillators for example with a rather poor frequency accuracy (10 ppm), the time of refresh should be roughly about 10 μsec.

All receiving stations are capable to detect the synchronization sequence thanks to the presence of a correlation filter which is matched to the synchronization trailer. In the proposed scheme each UWB receiver includes thus two correlation filters, as indicated in figure 4. The first of these filters is continuously searching for the synchronization trailer. This filter generates a peak in the presence of a synchronization trailer at its input. When conditions are favourable, i.e. required SNR is met, the peak exceeds a given threshold, and triggers the detection circuit. The amplitude of the peak corresponds to an integrated energy over all pulses in the synchronization trailer. For fixed pulse energy, the synchronization trailer must therefore contain a sufficient number M of pulses capable of guaranteeing a low probability of misdetection. Moreover, in order to generate only one peak, the autocorrelation of the synchronization trailer must present only one maximum besides much smaller side lobes. Figure 5 displays a feasible autocorrelation function for the synchronization trailer.

The second filter is used for data extraction, and considers the information regarding the TH sequence. The two filters operate independently. When the synchronisation trailer is detected, the receiver starts decoding the data by sampling the output of the second correlation filter.

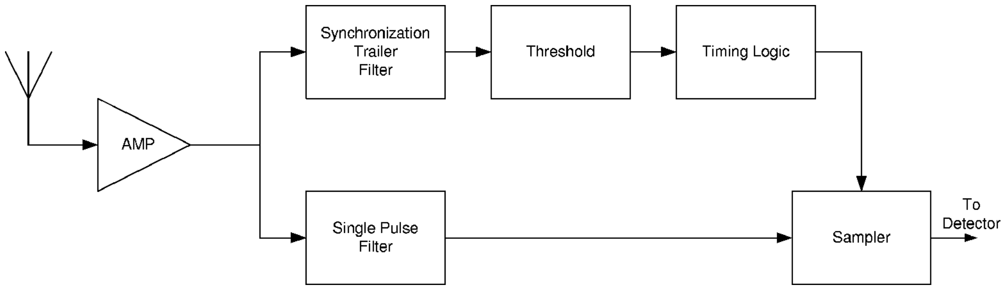


Figure 4. Receiver front end.

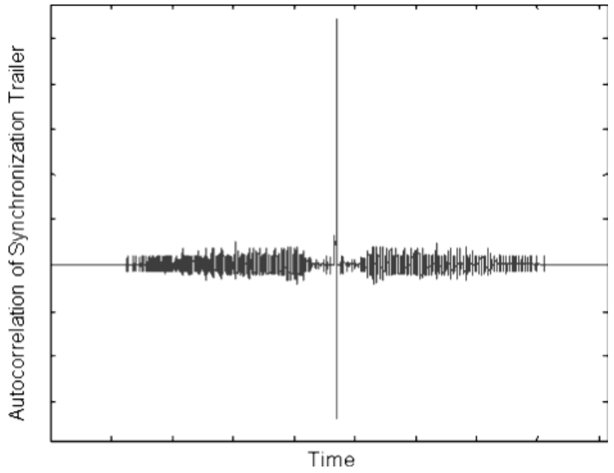


Figure 5. Autocorrelation function of the synchronization trailer.

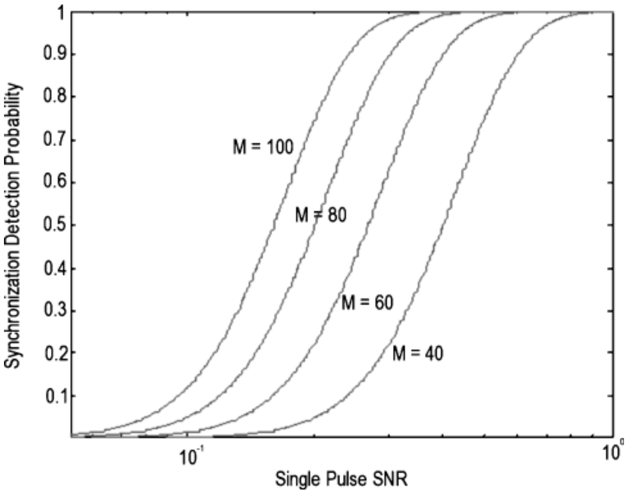


Figure 6. Synchronization detection probability over an AWGN channel for different lengths of the synchronization trailer, as indicated by M.

A rough appraisal of the requested M value was obtained by simulation. This number was as expected highly dependent upon many factors among which the requested SNR. For a wide range of applications estimated M values are in the range 40 to 100 pulses.

Figure 6 shows the synchronization detection probability in an AWGN channel as a function of SNR of a single pulse, and for different M values ranging from 30 to 100.

3. Medium access control: The (UWB)^2 protocol

UWB features with respect to MUI and synchronization as analyzed in the previous section formed the basis for the definition of an UWB tailored Medium Access Control protocol: (UWB)^2.

(UWB)^2 takes advantage for data transmission of the multiple access capabilities warranted by the TH Codes, and relies for the access to the common channel on the high MUI robustness provided by the processing gain of UWB. The proposed protocol also takes into account synchronization requirements.

(UWB)^2 is a multi-channel MAC protocol. Multi-channel access protocols have been widely investigated in the past, since the adoption of multiple channels may significantly increase the achievable throughput [17]. In multi-channel protocols the overall available resource is partitioned into a finite number of elements. Each element of the resource partition corresponds to a channel. According to the definition of resource, a channel can therefore correspond to:

1. A time slot, as in Time Division Multiple Access (TDMA);
2. A frequency band, as in Frequency Division Multiple Access (FDMA);
3. A code, as in Code Division Multiple Access (CDMA).

The design of an UWB MAC may adopt any of the above solutions. As described in Section, the IEEE 802.15.3a standard for example proposes a TDMA MAC for UWB [14]. TH-IR UWB, however, provides a straightforward partition of the resource in channels, each channel being associated to a TH code. The design of a multi-channel CDMA MAC protocol forms therefore the natural basis for the design of a MAC in TH-IR UWB.

Multi-channel CDMA MAC algorithms, commonly referred to as multi-code, have been intensively investigated for Direct Sequence (DS) CDMA networks. Among all we cite random CDMA access [18,21], and, more recently, Multi-Code Spread Slotted Aloha [8]. Note, however, that although in the last years most of the research efforts were focused on DS CDMA, Frequency Hopping (FH) CDMA and TH CDMA also provide viable solutions.

Performance of multi-code MAC protocols are limited by two factors:

1. MUI, caused by the contemporary transmission of different packets from different users on different codes;
2. collisions on the code, caused by the selection of the same code by two different transmitters within radio coverage.

Robustness of the system to MUI is determined by the cross correlation properties of the codes; The lower the cross correlation between different codes, the higher the number of possible simultaneous transmissions.

The effect of code collisions can be mitigated by adopting appropriate code selection protocols. The task of assigning codes to different transmitters in the same coverage area is a challenging issue in the design of distributed networks. Within this framework Sousa and Silvester [25] provided a thorough overview of possible code assignment solutions:

1. *Common code*: all terminals share the same code, relying on phase shifts between different links for avoiding code collisions.
2. *Receiver code*: each terminal has a unique code for receiving, and the transmitter tunes on the code of the intended receiver for transmitting a packet.

3. *Transmitter code*: each terminal has an unique code for transmitting, and the receiver tunes on the code of the transmitter for receiving a packet.
4. *Hybrid*: a combination of the above schemes.

The Common code scheme is sort of a limit case for a multi-code protocol, since no real multi-code capability is exploited. If phase shifts are too small, this solution collapses into the single Aloha channel. The Receiver code scheme has the main advantage of reducing receiver complexity, since a terminal must only listen to its receiving code. On the other hand, multiple transmissions involving the same receiver may likely result in collisions, since the same code is adopted by all transmitters. Oppositely the Transmitter code scheme avoids collisions at the receiver, since each transmitter uses its own code, but requires in principle a receiver to be capable of listening to all possible codes in the network.

Hybrid schemes allow a trade-off between the above conditions. A hybrid scheme may foresee the use for signaling of either the Receiver or Common code schemes over which the receiver can read the information about the code which will be used for data. A Transmitter code scheme may then be used for data.

When the set of codes is limited, however, the Transmitter code scheme may be subject to collisions due to reassignment of the same code. In this case, a code assignment protocol is required for optimizing the use of the limited set of available codes. An example of such a protocol is presented in [11], where a distributed assignment protocol is proposed for CDMA multihop networks. In this protocol if code C is used by terminal T, code C is never selected within a two-hops range from T.

The $(UWB)^2$ protocol applies the multi-code concept to the specific case of a TH-IR UWB system. $(UWB)^2$ adopts a Hybrid scheme based on the combination of a common control channel, provided by a Common TH code, with dedicated data channels associated to Transmitter TH codes. The adoption of a Hybrid scheme can be motivated as follows:

1. It simplifies the receiver structure, since data transmissions (and corresponding TH codes) are first communicated on the control channel;
2. It provides a common channel for broadcasting. This is a key property for the operation of higher layers protocols. Broadcast messages are for example required for routing and distributed positioning protocols.

As regards code assignment, a unique association between MAC ID and Transmitter Code can be obtained by adopting the algorithm described in [13] which avoids implementing a distributed code assignment protocol.

$(UWB)^2$ does not assume that synchronization between transmitter and receiver is available at the beginning of packet transmission, because of clock drifts in each terminal. As a consequence, a synchronization trailer long enough to guarantee the requested synchronization probability is added to the packet. The length of the trailer depends on current network conditions, and is provided to the MAC by the synchronization logic.

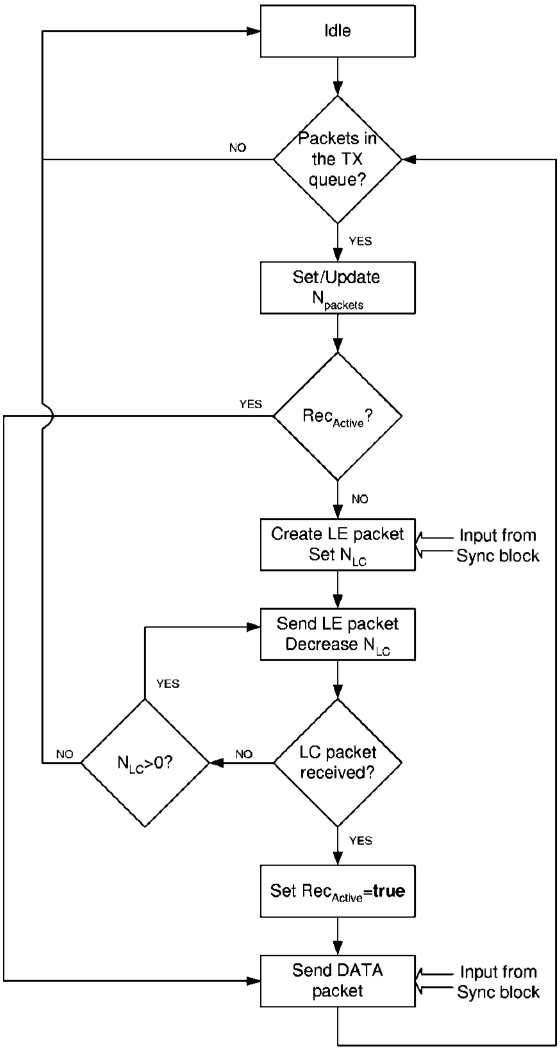


Figure 7. Flow chart of transmission procedure.

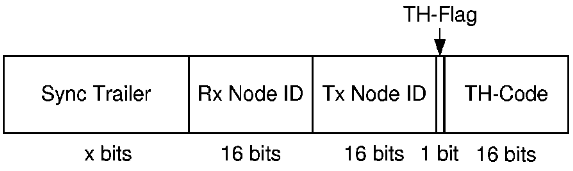


Figure 8. Link Establish (LE) packet structure.

$(UWB)^2$ also exploits the ranging capability offered by UWB. Distance information between transmitter and receiver is in fact collected during control packets exchange. Such information can enable optimizations of several MAC features, and allow the introduction of new functions, such as distributed positioning.

Procedures adopted in $(UWB)^2$ for transmitting and receiving packets are described below. The procedures have two main objectives:

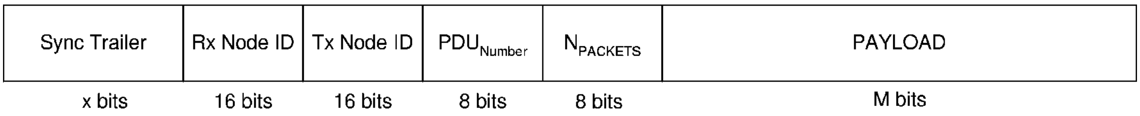


Figure 9. Data packet structure.

1. To exchange information such as the adopted synchronization trailer, i.e. hopping sequence and length;
2. To perform ranging. Since no common time reference is available, a two way handshake is required to collect distance information by estimating the round-trip-time of signals in the air.

It is assumed that, at each terminal T, MAC Protocol Data Units (MACPDUs) resulting from the segmentation/concatenation of MAC Service Data Units (MACSDUs) are stored in a transmit queue. It is also assumed that T is able to determine how many MACPDUs in the queue are directed to a given receiver R.

3.1. Transmission procedure

Figure 7 contains the flow chart of the transmission procedure. Terminal T periodically checks the status of the transmit queue. Detection of one or more MACPDUs triggers the transmission procedure which can be described as follows:

1. The ID of the intended receiver R is extracted from the first PDU in the queue;
2. T determines the number N_{PACKETS} of MACPDUs in the queue directed to R;
3. T checks if other MACPDUs were sent to R in the last T_{ACTIVE} seconds. If this is the case, T considers R as an Active receiver, and moves to step 5 of the procedure;
4. If R is not an Active receiver, T generates a Link Establish (LE) packet. The LE packet is composed by the following fields (see figure 8):
   - SyncTrailer—Used for synchronization purposes
   - TxNodeID—The MAC ID of transmitter T
   - RxNodeID—The MAC ID of receiver R
   - TH_Flag—This flag is set to **true** if the standard TH code associated to TxNodeID will be adopted for transmission of data PDUs. The flag is set to **false** if a different TH code is going to be adopted.
   - TH Code (optional)—If the TH_Flag is set to **false**, the information on the TH-code to be adopted is provided in this field.
5. Terminal T sends the LE packet and waits for a Link Confirm (LC) response packet from R.
6. If the LC packet is not received within a time T_{LC}, the LE packet is re-transmitted for a maximum of N_{LC} times, before the transmission of the MACPDU is assumed to be failed.
7. After receiving the LC packet, T switches to the TH code declared in the LE packet and transmits the data packet. The data packet is composed of (figure 9):
   - SyncTrailer—Used for synchronization purposes
   - Header, including the fields TxNodeID, RxNodeID, $\text{PDU}_{\text{Number}}$ and $\text{N}_{\text{PACKETS}}$
   - Payload, containing data information.
8. Once the transmission is completed, T checks again the status of the data queue, and repeats the procedure until all MACPDUs in the transmit queue are served.

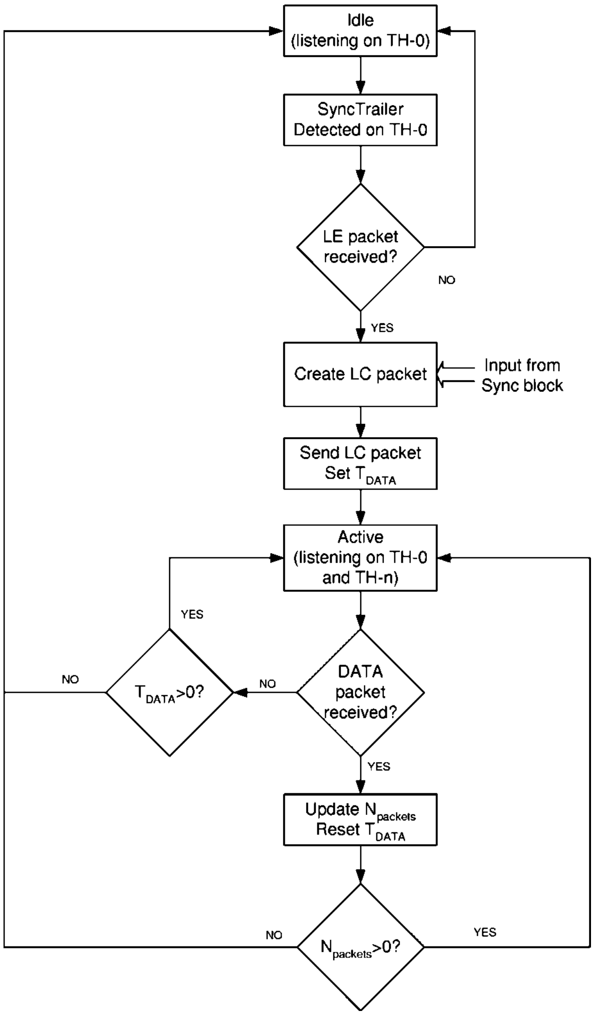


Figure 10. Flow chart of reception procedure.

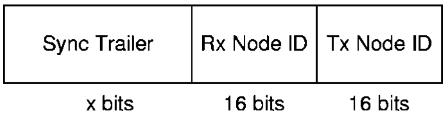


Figure 11. Link Confirm (LC) packet structure.

3.2. Reception procedure

Figure 10 contains the flow chart of the reception procedure. A terminal R in Idle state listens to the Common TH code. When a SyncTrailer is detected, R performs the following procedure.

1. R checks the RxNodeID field. If the value in the field is neither the MAC ID of R nor the broadcast ID, the reception is aborted and the reception procedure ends;
2. Since in the following we are not considering broadcast packets, let us assume that the RxNodeID contains the MAC ID of R. In this case, since R is assumed in Idle state, MACPDUs directed to this terminal will necessarily be LE packets;
3. Following the reception of a LE packet, R creates a LC packet, composed of (figure 11):
    - SyncTrailer—Used for synchronization purposes
    - TxNodeID—The MAC ID of T
    - RxNodeID—The MAC ID of R
4. R sends the LC packet and moves in the Active state, listening on the TH code indicated in the LE packet. If no data packet is received within a time T_{DATA} the receiver falls back to Idle state and the procedure ends.
5. When a data packet is received, R processes the payload, and extracts N_{PACKETS} from the header. If $N_{\mathrm{PACKETS}} > 0$, R remains in Active state, since at least N_{PACKETS} more data packets are expected to be received from T. If $N_{\mathrm{PACKETS}} = 0$, R goes back to the Idle state.

It should be noted that the above procedures are related to the setup of a single link. During the reception procedure for example R also keeps on listening to the common code. A terminal in fact can act as a receiver on one or more links while acting as a transmitter on other links.

Finally note that the exchange of LE/LC packets can also be triggered on a periodic basis for the purpose of updating distance information. This is likely to be the case for example if a distributed positioning protocol is adopted which relies on up-to-date distance estimations to build a network map.

4. Simulation results

The simulation scenario consisted in N terminals, randomly located in an area of $80 \times 80\ \mathrm{m}^2$ size. Each terminal was characterized by a radio transmission range of 120 meters which guarantees full connectivity between terminals. Each terminal generated MACPDUs to other terminals in the network following a Poisson process characterized by an average inter-arrival time T_{PDU}. The size of each MACPDU, with the format reported in figure 3, was set to $L = 2000$ bits. As regards UWB physical layer parameters, the pulse rate was set to 1 Mpulses/sec, $N_s = 1$, and $T_p = 1$ nsec.

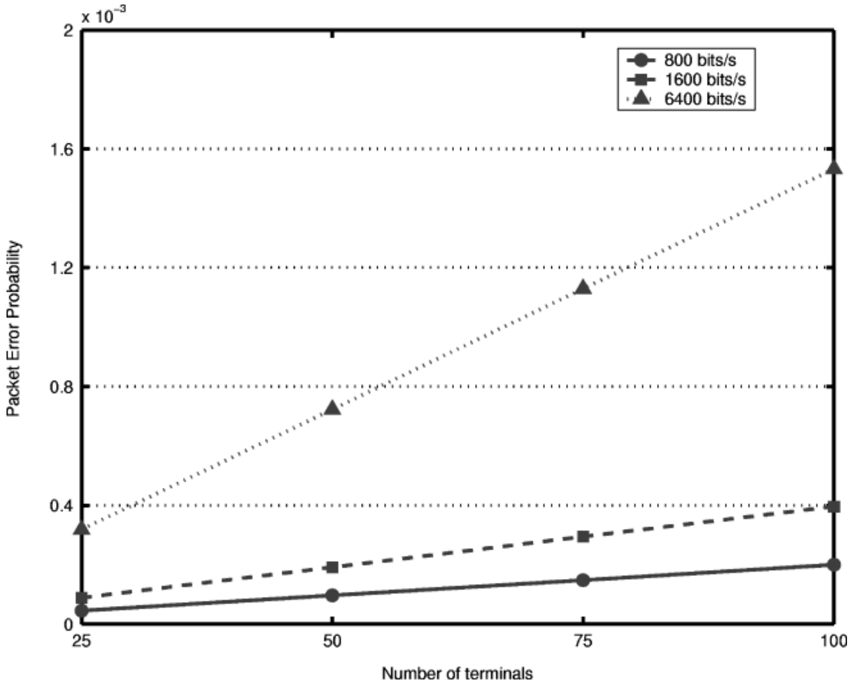


Figure 12. Packet Error Probability as a function of number of terminals for different data bit rates (circle: 800 b/s, square: 1600 b/s, triangle: 6400 b/s).

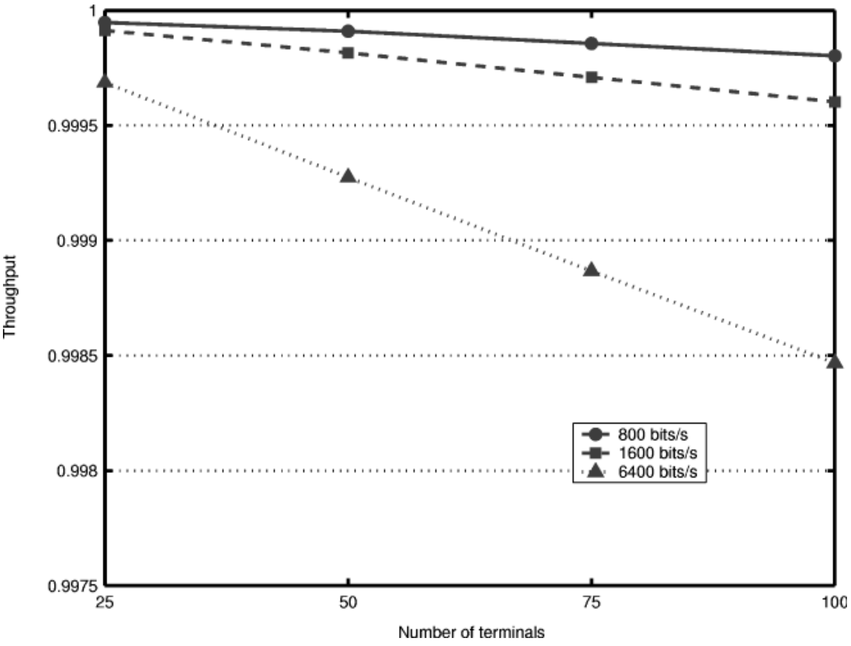


Figure 13. Throughput as a function of number of terminals for different data bit rates (circle: 800 b/s, square: 1600 b/s, triangle: 6400 b/s).

In the simulations we assumed all terminals to adopt the same synchronization sequence.

Performance of the $(\mathrm{UWB})^2$ protocol was evaluated for a number of terminals varying between 25 and 100, and for three different T_{PDU} values: 2.5 secs, 1.25 secs, and 0.3125 secs, corresponding to data rates of 800 bits/s, 1600 bits/s and 6400 bits/s, respectively.

Two performance indicators were considered. Throughput defined as the ratio between received MACPDUs and transmitted MACPDUs, and Packet Error Probability (PEP) based on the analytical model derived in Section 2. Following the approach of Section 2, no correction capability was considered, and we assumed that all bits in a packet to be correct, for a packet to be correct. During simulations, a real-time evaluation of P_U rather than the average value P_U of equation (5) was adopted for computing the probability of pulse collision. As a consequence, the Packet Error Probability was evaluated as follows:

$$\mathrm{PEP} = 1 - \prod_{i=0}^{L-1} (1 - \mathrm{Prob}_{\mathrm{BitError}}(i)) \tag{9}$$

where $\mathrm{Prob}_{\mathrm{BitError}}(\mathrm{i})$ is the error probability for the i-th bit in the packet, as defined in (7).

The measured values for PEP and Throughput are presented in figures 12 and 13, respectively. Figure 12 shows that for the three considered data rates the PEP remains below 1.6×10^{-3} for as much as 100 users.

The low PEP values are reflected in the analysis of the measured Throughput. Figure 13 shows that measured Throughput was higher than 0.998 in all simulation cases.

Note that all results included the effect of control traffic, formed by the LE/LC packets exchanged to perform ranging.

5. Conclusions and future work

In this paper we proposed a Medium Access Control protocol for UWB radio networks. The proposed protocol named $(\mathrm{UWB})^2$ exploits the large processing gain of UWB, and is based on a synchronization scheme which foresees the presence of a synchronization trailer in each transmitted packet. Each node receiver has a structure such that continuous tracking of the synchronization sequence can be performed. Performance analysis of the synchronization tracking mechanism, based on both analytical derivation and simulation data, showed that when the number of pulses in the synchronization sequence is sufficient, a fairly high probability of successful synchronization detection is achieved, also in the presence of several users and MUI. Based on this result we proposed and implemented a MAC protocol following a pure Aloha approach. The protocol named $(\mathrm{UWB})^2$ adopts a hybrid scheme which combines a common control channel, provided by a common TH-code, with dedicated data channels associated to transmitter TH-codes. $(\mathrm{UWB})^2$ does not require complex interference control mechanisms. Results of simulations indicate that $(\mathrm{UWB})^2$ can be successfully applied when the number of users spans from a few tens to about one hundred, for data rates ranging from a few thousands to a few hundreds of bits per second. Results show in fact that data transfers experience a low Packet Error Rate, leading to a network throughput above 99.8% in all considered simulation settings. Such achievement confirms that $(\mathrm{UWB})^2$ is a suitable and straightforward solution for large networks of terminals transmitting at low bit rates.

The above results will form the basis for future developments of the $(\mathrm{UWB})^2$ protocol. Our future work will concentrate on applications of the proposed algorithm in the case of non-AWGN channels, i.e. under complex propagation conditions, and possibly increased bit-rates.

With reference to radio propagation, a detailed analysis of the effect of a realistic UWB channel on pulse shape is required in order to better estimate the probability of misdetection for both synchronization sequence and data bits at the receiver. In particular, pulse temporal spreading in the presence of propagation obstacles has recently been shown to be crucial [20], and should be taken into account in our model for improving characterization of the event of pulse collision at the receiver. A precise analysis of the distortions experienced by transmitted pulses is not an easy task; A few studies on UWB propagation showed that the above problem can be solved by using analytical methods as for example numerical integration (see for example [20]). When considering propagation in a realistic scenario, an accurate model of path loss is also required for characterizing the near-far effect experienced by each receiver in the presence of multiple devices transmitting without power control. A quantitative analysis of the interference suffered by UWB receivers from narrow-band interferers should finally be included for determining the robustness of the proposed synchronization procedure in a multi-network scenario.

As far as multiple access capabilities of the $(\mathrm{UWB})^2$ approach are concerned, further investigations are required for better evaluating and eventually quantifying the limitations of the Aloha scheme when considering applications requesting QoS and high bit rate. In both cases, system robustness to MUI cannot rely only on the processing gain which is provided by the underlying physical layer, and additional mechanisms for power control and error protection must be introduced in order to avoid an unacceptable increase of packet loss. According to the conventional theory of CDMA communications, system robustness to MUI cannot be improved by simply allowing devices to transmit at a higher power. Interference can be controlled at the MAC layer in fact only by increasing coordination among users.

In the presence of increased number of errors at the physical layer, the MAC can also react by introducing error protection mechanisms on each transmitted data unit. In particular, mechanisms for either retransmission (i.e. Automatic Repeat on reQuest, ARQ) or error correction (i.e. Forward Error Correction, FEC), or both, may be implemented in order to improve robustness of data packets to both MUI and narrow-band interference. ARQ mechanisms are based on the repetition of corrupted MACPDUs [4], while FEC schemes introduce redundancy in each MACPDU [22]. ARQ based solutions introduce delays on transmission; On the other hand, the FEC approach has the drawback of increasing overhead transmission, and therefore introduces efficiency loss. Consequently, transmission efficiency can only be guaranteed when the MAC protocol is capable of adjusting error protection according to both channel performance, and application requirements. An analytical approach for selecting and designing optimum error protection schemes at the MAC layer was proposed in [12]. Our goal will be thus to introduce such a mechanism in the $(\mathrm{UWB})^2$ protocol when considering scenarios with several devices transmitting at high bit rates.

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