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MANAGING IMPULSIVE INTERFERENCE IN IMPULSE RADIO UWB NETWORKS

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Wireless sensor networks are ideally built on low-cost, low-complexity nodes that have a low power consumption to guarantee a long network lifetime. These are all properties that can potentially be achieved with impulse radio ultra-wide band (IR-UWB). In addition, IR-UWB has a fine timing resolution enabling accurate ranging and localization capabilities. For all these reasons, IR-UWB is an extremely interesting physical layer technology for wireless sensor networks. In this article, we consider the management of impulsive interference in IR-UWB networks. Impulsive interference is due to uncoordinated concurrent transmissions. It occurs, for instance, when several independent piconets operate in close vicinity and is also present in some MAC layer proposals that allow concurrent transmissions. If not properly addressed, impulsive interference can severely affect the throughput and energy consumption of an IR-UWB network; as such, it already needs to be taken into account in the design phase. First, we show that impulsive interference is a serious concern for IR-UWB networks. Second, we present techniques at the physical layer and at the link layer to cope with and combat such interference efficiently. Finally, we present DCC-MAC as an example of an interference-aware design.

1. INTRODUCTION

For the design of wireless networks, there are two choices with respect to interference: we can design a system that tries to control or even prevent interference, or we can intentionally allow interference. Systems that let interference happen use some form of adaptability to deal with the constantly changing environment. Systems to control or prevent interference use mechanisms such as tight power control, orthogonal communication channels, or mutual exclusion [1].

However, even in systems designed to control interference, there are always numerous external factors that are beyond the control of the system designer. For instance, there might be coexisting, non-coordinated piconets that interfere with each other. This external interference is difficult to foresee, and adaptive mechanisms to cope with it are required.

We consider non-coordinated systems based on impulse radio UWB (IR-UWB) physical layers that allow concurrent transmissions without power control [2], [3]. Data transmission at the physical layer occurs in sequences of very short pulses[1] with a large pulse repetition time (PRT). The most frequently used physical layer model [4] is illustrated in Fig. 1 and briefly introduced in the following. Time is divided into frames of length T_f. Each user transmits one pulse of length T_p per frame. To provide some multi-access capability, a frame is further subdivided into non-overlapping chips of length T_c, where $T_c \geq T_p$. Each user chooses the chip in which to transmit its pulse randomly according to a (pseudo-random) *time-hopping sequence* (THS).

Such systems are subject to impulsive, non-Gaussian interference created by the system itself, or by other, similar systems. On Fig. 2, we can clearly observe the detrimental effect of impulsive interference on an IR-UWB physical layer. Further, like any other UWB system [5], they have to coexist with existing narrowband technologies like 802.11. Managing interference to and from such coexisting technologies has been extensively studied and is out of the scope of this article. In this paper, we concentrate on impulsive interference. The main source of impulsive interference in IR-UWB systems are pulse collisions between concurrently transmitting sources. Pulse collisions occur even though nodes from different piconets generally use different THSs. This is due to the fact that THSs in IR-UWB are usually not orthogonal

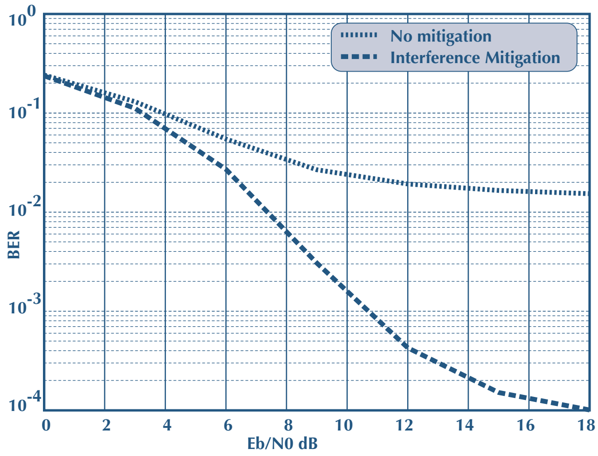

Figure 2: In uncoordinated IR-UWB networks, some form of interference mitigation at the physical layer is needed. We show the bit error rate (BER) versus signal-to-noise ratio at the receiver for a system with and without interference mitigation. The mitigation scheme used here is the one using interference modeling (further described in Section 2.3.2); the scenario for the simulation is the same as in Fig. 4. It can clearly be seen that the performance degradation is huge when not mitigating the effect of interference.
Interference mitigation at the physical layer is discussed in Section 2.2, and a possible solution is given in Section 2.3.

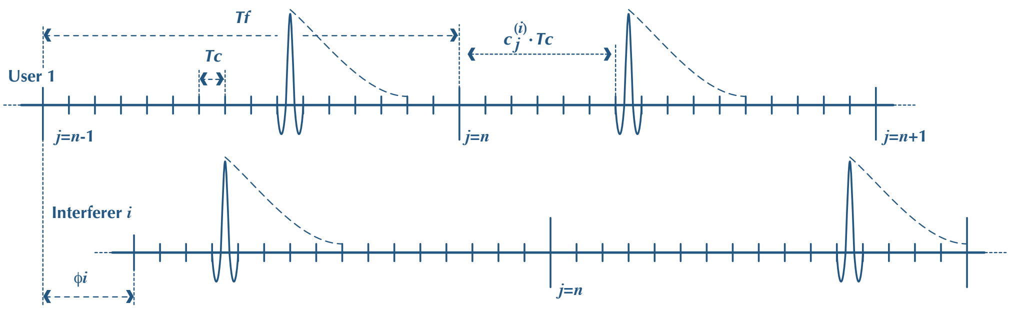

Figure 1: Illustration of the definitions. $c_j^{(i)}$ denotes the time-hopping sequence of user i and Φ_i is the delay between user i and user 1. The dashed curve following the pulses represents the multipath propagation.

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[1] Or short bursts of short pulses

and therefore do not completely prevent collisions. Furthermore, even if they were perfectly orthogonal, a tight synchronization between all the nodes in different piconets would be needed to prevent interference caused by misaligned THSs.

We focus on techniques and schemes that are used to react and adapt to interference. We do not discuss protocols or techniques that try to prevent or control interference (see [1] and the references therein). A multipath propagation channel at the physical layer further worsens the situation. The larger the delay spread of the channel, the more a pulse is spread in time. This increases the probability of pulse collisions. As IR-UWB systems are likely to be used in environments exhibiting severe multipath (indoor, factories, etc.), this is a serious issue. Another factor that increases the probability of pulse collisions is the number of users trying to transmit simultaneously. Even in systems with a generally low duty-cycle, it can happen that a lot of users access the channel at the same time. An example is a sensor network detecting a fire outbreak. In this case, a specific event triggers simultaneous transmissions from a large number of nodes.

Finally, one additional important factor concerning interference is the near-far effect. As the systems under consideration do not make use of power control, interferers close to the receiver might not have a signal of much higher strength than that of the user of interest. To ensure that small portions of these high power signals do not predominate the received signal, they have to be mitigated to prevent a huge performance loss.

Note that in a mobile ad hoc network, not only interference, but also the variable environment calls for adaptability of the system. Additionally, systems that try to prevent interference usually need tighter control than systems that let interference happen. This is often undesirable in an uncoordinated ad hoc network.

Impulsive interference in IR-UWB systems reduces the signal-to-interference-and-noise ratio (SINR) at the receiver. It affects the quality of the radio link, producing more packet losses, which result in an overall rate reduction and an increased energy consumption. Interference has a large impact on the system performance and needs to be taken into account as early as in the design phase. As we further show in this paper, interference management is a cross-layer issue. It has to be dealt with at the physical layer level as well as at the link layer level.

On the physical layer, some form of interference mitigation (Section 2.2) is needed to deal with the near-far effect. The benefits of an interference mitigation scheme are depicted in Fig. 2.

On the link layer, adaptive retransmission techniques must be used. Also, the overall rate of a source has to be variable in order to be adapted to the current level of interference at the receiver. Systems with a fixed rate must be designed in order to sustain the worst possible operating conditions, typically a poor channel between a source and its destination. This in turn imposes a low overall rate. Systems with an adaptive rate can take advantage of good channel conditions to transmit with a higher rate. In the case of degraded channel conditions, their adaptability prevents complete communication outages.

We do not discuss the effect of these schemes on energy consumption. There is, of course, a trade-off. A better system performance reduces the number of retransmissions and hence decreases the energy consumption. On the other hand, more complex transceiver designs increase the energy-consumption.

The organization of this paper is as follows. In Section 2, we present techniques to combat interference on the physical layer. In Section 3, we discuss link layer techniques to cope with interference. In Section 4, the DCC-MAC protocol [2] is presented as a concrete example of an interference aware design which is a rate-adaptive medium access control (MAC) protocol for IR-UWB networks. Finally, we conclude the paper in Section 5.

2. COMBATING INTERFERENCE AT THE PHYSICAL LAYER

Combating interference matters to all functions provided by the physical layer, be it decoding, channel estimation, or timing acquisition and detection. We will present some possible solutions for all of these functions in Section 2.3. Currently used techniques to combat interference on the physical layer can be divided into two classes, both of which are shortly discussed in the following.

2.1. Techniques based on joint decoding

These are extensions or adaptations to UWB of classical, well-established techniques that are also used in other systems like CDMA [6]. They aim at cancelling or suppressing interference by jointly estimating and decoding the signals of a large number of users. For example, a near-far interferer would be jointly received instead of being treated as interference. This annihilates the near-far effect and makes joint decoding potentially attractive. However, an optimal joint processing of all users [7] is mostly not possible due to its very high complexity. Therefore, suboptimal methods like minimum mean-square error (MMSE) multi-user detectors (MUD) or receivers employing successive interference cancellation (SIC) are used [8]. All of these methods share the common factor that the receiver has to acquire and actively decode each of the users. This might be perfectly suited for a centrally coordinated and synchronized system, where a base station communicates with a large number of users at the same time. However, with a distributed IR-UWB system, synchronizing the receiver with all the users is extremely complex and impractical. In addition, the complexity of the decoding operation is excessively high.

2.2. Techniques based on interference mitigation

In contrast to joint decoding, signals from interfering users are treated as a common interference term. Techniques based on interference mitigation try to reduce this interference term and to mitigate and reduce its effect on the performance of the physical layer. We distinguish two possible options, interference modeling and thresholding:

2.2.1. Interference modeling

The interference term is assumed to follow an underlying statistical model. The background noise is often directly incorporated in the interference model. A receiver using interference modeling proceeds in two steps. It first tries to estimate the model parameters. In a second step, this model is exploited to mitigate the effect of the interference. Modeling interference is important as it has been shown that simply assuming it to be Gaussian is not accurate [9].

In order to estimate the parameters of the model, techniques based on interference modeling can either follow a data-aided [10], [11], [12] or a blind approach [10]. In the data-aided approach, a training sequence known to the receiver is used. The receiver estimates the statistics of the interference model exploiting the knowledge about the training sequence. In the blind (non-data-aided) approach, the receiver jointly estimates the model parameters as well as the unknown data sequence.

2.2.2. Thresholding

A simple thresholding mechanism can be applied. Samples of the received signal that have an amplitude exceeding a certain threshold are assumed to have a large interference contribution[2], [13], [14], [8]. Although thresholding is easy to implement, an issue common to all thresholding schemes is the determination of the optimal threshold. This is often left as an open issue, or it boils down to assuming an AWGN multi-user interference (MUI) model and setting the threshold based on the estimated average received noise power [13].

2.3 MUI-aware physical layer system design proposals

We now present some proposals for physical layer core functionalities that were specifically designed for asynchronous IR-UWB systems subject to impulsive interference and that use the above mentioned techniques.

2.3.1. Timing acquisition and detection

In conventional detection methods, the transmitter prepends each packet with an acquisition preamble known to the receiver. The receiver correlates the received signal with this acquisition preamble and performs a threshold check. If the output of the correlator exceeds a certain threshold, a good match between the received signal and the acquisition preamble is assumed, and detection of the packet is declared. These methods have a severe drawback when MUI is present. If one of the pulses of the acquisition preamble at the receiver is aligned with a pulse of a near-by interferer, this interfering pulse can affect the correlation significantly. Consequently, a small number of aligned interfering pulses can dominate the output of the correlator and lead to a wrong detection. In [14], a power independent detection (PID) method that addresses this problem was proposed. As for the conventional methods, the PID uses thresholding. However, it splits the correlation with the whole acquisition preamble into a set of elementary correlations. Each elementary correlation corresponds to only one pulse of the acquisition preamble. A first threshold is applied at the output of each elementary correlation. If the energy captured by the elementary correlation exceeds the first threshold, detection of the corresponding pulse is declared. A second threshold is then applied to the number of detected pulses. If the number of detected pulses exceeds the second threshold, detection of the packet is declared. This procedure makes sure that all the pulses of the acquisition preamble contribute equally to the final decision. This procedure is therefore resistant to near-far interference.

2.3.2. Channel estimation and decoding

As already mentioned, a Gaussian model is not well suited to model MUI in an IR-UWB system. A popular non-Gaussian model is the Gaussian Mixture Model (GMM). The GMM assumes that the interference has an underlying probability distribution formed by a mixture of Gaussians with different variances. Each interference term is then assumed to be generated by one of these mixture components. The GMM seeks to classify each sample and typically attributes samples with high interference to mixture components with high variances. In [11], the GMM is proposed as a MUI model for IR-UWB. We will show how to perform channel and interference statistics estimation based on this model using a data-aided approach.

The GMM assumes that the mixture components are independently chosen. However, due to the multipath nature of the channel, this is not necessarily true, as samples with a high interference level are likely to occur in bursts. Therefore, we propose [12] to introduce correlation by modeling the sequence of mixture components with a homogeneous Markov chain. The resulting MUI model is a hidden Markov model (HMM), where each state is associated with a Gaussian output distribution. The GMM is just a special case of the more general HMM, where the choice of the next state is independent of the current state[2]. We find that the HMM is effectively better in modeling MUI than the GMM. However, the performance difference is not that huge and comes at the cost of increased complexity.

In [12], we also propose a coherent RAKE receiver that makes use of a combination of thresholding and interference modeling to mitigate interference in the decoding process and accounts for the multipath nature of UWB channels. Interference modeling is done using a data-aided approach. Let us assume for simplicity that the interference model (GMM or HMM) only has two states, s_1 and s_2, where s_1 corresponds to a low interference level and s_2 to a high interference level. The receiver proceeds in two steps. In a training step, the channel coefficients as well as the variances, $\sigma_{s_1}^2$ and $\sigma_{s_2}^2$, associated with each of the two states, are estimated based on the known training sequence. In the subsequent data reception step, the receiver estimates for each sample y_n the probability $\gamma_{s_1}(n)$ that it has an interference term generated by state s_1[3]. Before passing the received samples to the decoder, the receiver multiplies each sample with the following weighting vector:

$$w(n) = \frac{\gamma_{s_1}(n)}{\sigma_{s_1}^2} + \frac{\gamma_{s_2}(n)}{\sigma_{s_2}^2}$$

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[2] The reader is invited to read [12] for a more mathematically rigorous definition of the respective interference models.

[3] Here we only consider a two state model, so the probability that the interference term of y_n was generated by s_2 is of course $\gamma_{s_2}(n)=1-\gamma_{s_1}(n)$.

Consequently, samples with an interference term that stems with high probability from s_2 get penalized through the factor $w(n)$. This ensures that samples with high interference do not contribute excessively to the decision made by the decoder. (Note the similarity to the power independent detection method described in Section 2.3.1). The effect of applying this weighting factor is shown in Fig. 3. Our coherent RAKE receiver also employs thresholding in addition to the interference modeling procedure described before. This is necessary in a data-aided approach since we are facing three different interference scenarios, only two of which are resolved by interference modeling. If interference occurs during packet reception, it must fall into one of the following three categories:

1. interference is present during both training and data reception (type 1)
2. interference is present during training only (type 2)
3. interference is present during data reception only (type 3)

Interference of type 1 is taken care of by interference modeling. Ideally, we estimate the interference during the training phase and then deal with it during data reception as explained above. Interference of type 2 should do even less harm; we have estimated it, but it is not present during data reception. Interference of type 3 is more difficult to tackle since it is not present during training. Therefore, the estimated variances of the interference term will be rather small (on the order of the background noise variance). Samples with a lot of interference will then still get a relatively high weight.

Hence, we propose the following thresholding mechanism. After the training phase, we determine the largest of the estimated variances. In the case of the two-state model discussed here, this is σ_{s_2}. We then determine a threshold ν, such that $P(X \geq \nu) \leq \varepsilon$, where $X \sim N(0, \sigma_{s_2})$, and ε is some predetermined small probability. We then erase the samples with an estimated interference and noise term exceeding the threshold ν by setting $\gamma_{s_1}(n) = \gamma_{s_2}(n) = 0$ for these samples. This ensures that the samples that cannot be explained by the estimated interference model with high probability do not contribute to the decision made by the decoder. Interference of type 3 is thus mitigated by detecting a deviation from the estimated model. A similar thresholding approach, rejecting samples suffering from high interference, has

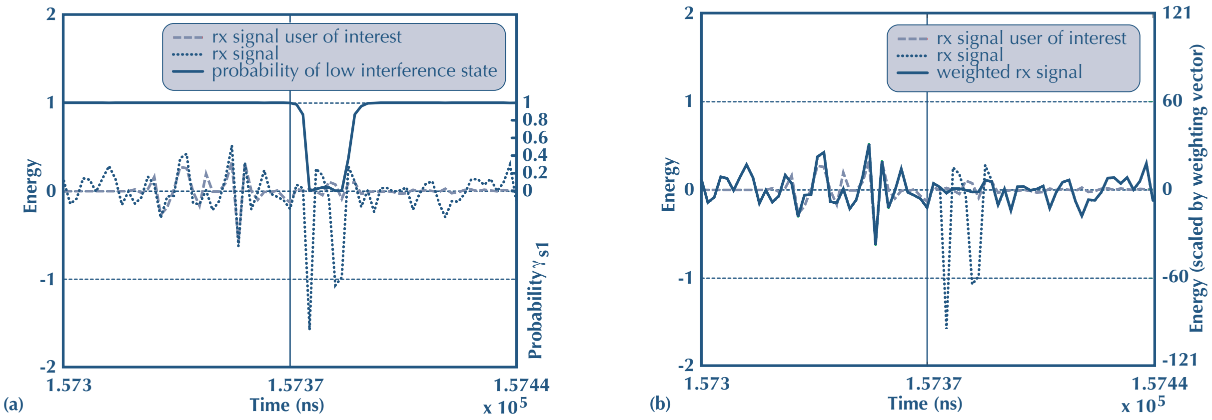

Figure 3: Here we show how an algorithm based on interference modeling performs interference mitigation. A two-state hidden Markov model is assumed for the MUI. In (a), one pulse of the received signal and its component corresponding to the user of interest is shown. For each sample, the receiver estimates the probability that it has a low contribution from interfering users (low interference state) or that it is polluted with a high interference term (high interference state). The estimated probability of being in the low interference state is also shown in the left figure. We can see that the algorithm nicely identifies the part that suffers from a high interference term. Based on this estimation, the receiver designs a weight vector that is applied to the received signal. Diagram (b) additionally shows the received signal after it has been multiplied with the weighting vector, and we can see that the MUI has been successfully removed.

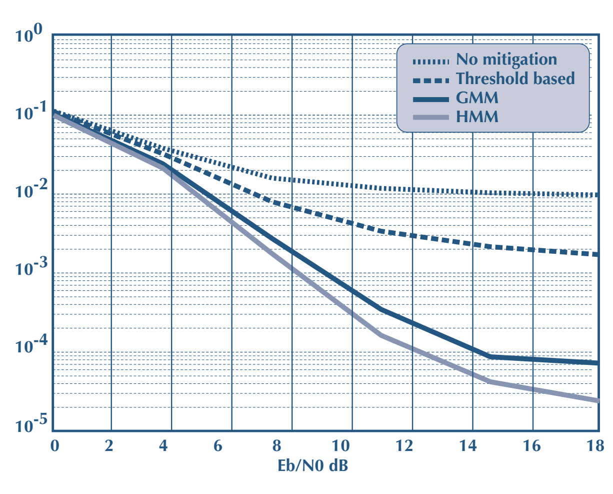

Figure 4: We compare our interference mitigation technique with a receiver that neglects multi-user interference (MUI) completely and with a receiver performing only simple thresholding. Physical layer packets are generated according to a Poisson process at half the peak data rate. The channel model we simulate is the 802.15.4a indoor NLOS model. Further, we have four near interferers with power levels of 10dB, 13dB, 16dB and 20dB with respect to the user of interest. It can be seen, that the performance gain from modeling the interference is significant. Using the more sophisticated HMM to characterize MUI gives an additional gain compared to that given the GMM model

been proposed in [8] for MUD in a synchronous UWB system, and in [13], [2] as a stand-alone method without interference modeling and without neglecting the multipath nature of the UWB channel. The performance gain of our proposal over these simple thresholding schemes can be seen in Fig. 4.

3. MANAGING INTERFERENCE AT THE LINK LAYER

In this section, we discuss several link-layer techniques that can be used to react and adapt to interference. Link layer techniques control transmission parameters and the retransmission behavior at the sender. Their goal is to adapt to the level of interference experienced at the receiver. When the interference at the receiver is low, adaptive transmission techniques allow for the increase of the throughput. On the other hand, when interference at the receiver is high, adaptive techniques avoid communication outages and ensure a minimum throughput.

In the case of IR-UWB communications, the transmission parameters to adapt can be the modulation order (number of bits per symbol), the power, the rate of the channel code, or the processing gain.

In order to adapt to these parameters, the transmitter must have an estimate of the level of interference at its intended receiver. In the context of uncoordinated networks, most techniques make use of feedback information from the receiver to the sender. Feedback information from the receiver can take various forms. It is often a function of the SINR. Several other examples can be found in [15]. However, with a UWB physical layer, measuring the SINR is difficult in practice due to the very low transmit power of UWB signals. For instance, the DCC-MAC protocol discussed in Section 4 relies on information produced by the channel decoder rather than on physical layer measurements.

3.1 Adaptation of the transmission parameters to the level of interference

Adaptive modulation [16] allows for the efficient adaption of the spectral efficiency to the level of interference. Adaptive modulation essentially varies the number of bits per symbols. In the case of IR-UWB, a simple and efficient technique is to use M-ary PPM [17]. A further technique is the use of joint modulation and coding, such as bit-interleaved coded modulation (BICM) [18], [19]. Even in the presence of multi-user interference (MUI), such a technique can considerably increase the throughput of an IR-UWB link [20].

The amount of redundancy of the channel code, and hence the rate, can be adapted to the level of interference. Practical schemes such as rate-compatible punctured convolutional (RCPC) codes [21] can be used. One of their main advantages is that only one decoder is necessary at the receiver for a given family of RCPC codes. Another interesting feature is that they can be used with incremental redundancy techniques (see Section 3.2). An issue that arises with IR-UWB physical layers and channel coding is the detrimental effect that impulsive interference can cause.

If soft-decision decoding is used, a large interference sample (for instance, in the case of near-far interference) can propagate through the trellis of the decoder and result in several decoding errors. However, if hard-decision decoding is used, this effect is prevented. But then, the performance when only regular Gaussian noise is present is impacted. Intuitively, the optimal decoding policy should consist of an adaptive combination of hard-decision when strong interferers are present and soft-decision otherwise [2]. Hence, an interference mitigation scheme (Section 2.2) should be used.

Adapting the processing gain for IR-UWB has been suggested in [17], [22]. It is possible to either change the average pulse repetition frequency or to change the number of pulses per symbol[4]. The issues of near-far interference also apply in this case. Changing the processing gain also has an impact on the average emitted power.

Note that adaptive modulation and adaptive channel coding are rate adaptation techniques. They are also procedures that are local to a single sender and receiver pair, that is, only communication between the source and the destination is required to perform them.

With power control [23], [24], a transmitter ensures that the received SINR at its destination remains higher than a given threshold. This threshold depends on the current level of interference at the receiver.

Contrary to adaptive modulation and adaptive channel coding, performing power control is a global procedure. Coordination is required not only between the source and its destination, but also with the neighbors of the transmitter. The transmitter should make sure that it does not destroy any ongoing transmission by reducing the SINR at receiving nodes in its vicinity. This requires the estimation of the channel gain between the transmitter and each node in the range of the transmitter.

The choice of rate adaptation and/or power control for IR-UWB networks is analyzed in [25]. When the objective is to maximize the overall throughput of the network, it turns out that the optimum is to use rate adaptation and no power control. If the primary objective is to minimize the energy consumption, this is still an open issue. Still, some results in [1] suggest that rate adaptation with no power control is not far from being optimal.

3.2. Adaptive retransmission techniques: Hybrid-ARQ with incremental redundancy

The techniques discussed in the previous section allows for the adaption of the parameters of the transmitted signal to the estimated level of interference at the receiver. However, there are two issues associated with these techniques. First, the feedback returned by the receiver is only an estimation of the level of interference at the receiver. Second, the level of interference can change significantly between the time the feedback is received and the time where the transmission occurs. In the first case, a solution is to include a safety margin. However, in the second case, an increase of the level of interference can arise and induce an error on the transmission between the source and the destination.

Hence, there is a need for an efficient retransmission procedure in case of a transmission failure. Such schemes have been extensively studied in the literature. They are denominated under the general term of Automatic Retransmission reQuest (ARQ). For an extensive overview of ARQ mechanism, the reader can consult [26], [15] and the references therein. In the remainder of this section, we will concentrate on adaptive mechanisms, the so-called hybrid-ARQ schemes.

In its simplest form, an ARQ scheme retransmits the same packet until successful reception occurs at the receiver. The feedback is binary and indicates whether or not the packet was properly received. However, this scheme will fail in the event of a strong and lasting interference; indeed, the data transmission will fail at each retransmission. Therefore, current ARQ techniques are adaptive. In most cases, the ARQ mechanism

[4] Pulse repetitions are a special case of channel coding. Indeed, it is nothing but a repetition code.

is combined with a variable-rate channel code. If the initial data transmission fails, the retransmission occurs with the data encoded with a more powerful code, i.e., at a lower rate[5].

A further improvement of this scheme can be obtained by using incremental redundancy. Instead of retransmitting the whole data encoded at a lower rate, only the coded information necessary to obtain the lower rate is sent. For instance, channel codes such as the RCPC code in [21], [27] can provide incremental redundancy. For a specific family of RCPC codes, a code of a given rate is a "subset" of all the codes with a higher rate.

Note that these schemes do not specify how the rate should be adapted. Hence, there is a large amount of freedom left for how the overall retransmission mechanism can be designed.
The design of an adaptive ARQ scheme is largely dictated by the flexibility of the channel code and by the type of feedback available between a receiver and the sender.

4. DCC-MAC: AN UNCOORDINATED MAC PROTOCOL FOR UWB NETWORKS WITH RATE ADAPTATION AND INTERFERENCE MITIGATION

In this section, we present the case study of a system designed to be interference-aware. We consider the organization of non-coordinated and asynchronous medium-access (MAC) protocol for UWB networks. One proposal is the DCC-MAC protocol [2]. DCC-MAC is an interference-aware design that is conceived to operate in a flawless manner in the presence of strong impulsive interference.

In order to compare the performance of DCC-MAC against a non interference-aware protocol, we compare DCC-MAC with the (UWB)^2 protocol. (UWB)^2 is a more recent proposal that is not interference-aware and does not support any mechanisms to combat impulsive interference. The main characteristics of the two protocols are summarized in Table 1.

DCC-MAC	(UWB)^2
Interference-aware	Non interference-aware
Interference mitigation	n/a
Rate adaptation	n/a
No control channel required, no RTS-CTS	Common control channel with RTS-CTS

Table 1: Main aspects and differences of the DCC-MAC and the (UWB)^2 protocol for non-coordinated impulse-radio UWB networks

In the following, we first describe the two main components of DCC-MAC that permit to combat interference, namely rate-adaptation and interference mitigation. In addition, we briefly describe the main aspects of our protocol. Then, we present simulation results that compare DCC-MAC with the (UWB)^2 protocol [3].

4.1. Rate-adaptation and interference mitigation in the DCC-MAC protocol

The main ingredients of DCC-MAC to combat interference are a rate-adaptation mechanism and an interference-mitigation scheme. Rate-adaptation is obtained by using RCPC channel codes. The modulation and the processing gain is fixed. The family of RCPC codes is the one described in [27]. It offers a set of twenty-five channel code rates that can be extended to thirty. Only one pair of channel code encoder and decoder is necessary. The rate-adaptation scheme is based on an additive-increase, multiplicative-decrease (AIMD) policy similar to what is used by TCP. Whenever a packet is successfully received, the destination takes advantage of the decoding process to estimate the maximum rate at which the data transmission could have occurred [2]. The receiver subtracts a safety margin and returns this information back to sender in the acknowledgment packet. Hence, in the case of DCC-MAC, the feedback consists of the estimated rate at which the next data transmission should take place.

Interference mitigation is used, albeit in the simple form of thresholding. The mechanism is similar to what is explained in Section 2.2. The transmission of data to a destination is performed using a time-hopping sequence unique to the destination. This time-hopping sequence can be created by seeding a pseudo-random number generator with a unique

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[5] A different modulation could be used, but this is hardly done in practice.

identifier for the destination. Such an identifier can be, for instance, the hardware address.

A typical transmission consists of a data packet transmission from the source to the destination, an acknowledgment sent back by the destination and the transmission of an IDLE packet from the source. Hence, it has a simple design that does not require any common control channel nor the use of any RTS-CTS type of handshake.

Along with a subtle control of timers and a careful use of time-hopping sequences, the IDLE packet is necessary for the protocol to operate properly in the absence of carrier-sensing as well as in multi-hop environments [2].

4.2. Performance evaluation of the DCC-MAC and (UWB)^2 protocols

In order to emphasize the importance of an interference-aware design, we compare the DCC-MAC protocol with the (UWB)^2 protocol [3]. Contrary to DCC-MAC, (UWB)^2 needs a common control channel and uses an RTS-CTS handshake to arbitrate access to a destination. (UWB)^2 uses neither power-control nor rate-adaptation. Interference is not mitigated at the physical layer. Table 1 summarizes the main aspects and differences of the two protocols.

We use the ns-2 simulator [28] with an extension for UWB physical layers. The code for the UWB extension is available online at [29]. The parameters correspond to a typical 802.15.4a scenario. The maximum rate of the physical layer is 1 Mbit/s. For every scenario, the link distance is 10 meters. The transport protocol is UDP. The throughput is the saturation throughput.

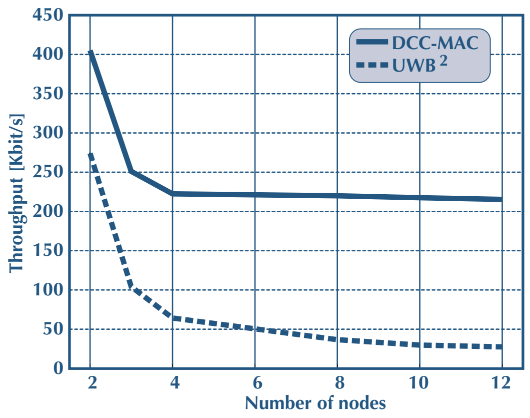

Figure 5: Performance of the DCC-MAC protocol and the (UWB)^2 protocol in a multi-hop scenario. The topology is a line of nodes with a link distance of 10 meters. The throughput is plotted against the number of nodes. The transmitter and receiver are located at each extremity of the line. The transport protocol is UDP. The DCC-MAC protocol clearly outperforms the (UWB)^2 protocol.

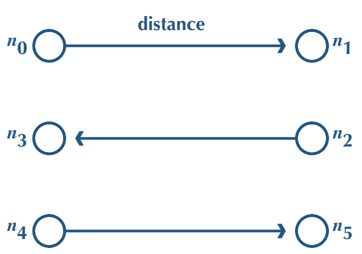

Figure 6: Near-far topology for six nodes, i.e., with three concurrent communication links. The link distance is d. The direction of the communication is alternated from one link to another.

In Fig. 5, the network throughput of the two protocols is compared in a multi-hop scenario. The topology is a line of n nodes where one extremity of the line sends to the other extremity. The throughput of (UWB)^2 drops dramatically as the number of hops increases. On the contrary, the throughput of DCC-MAC remains stable for more than three hops. In Fig. 7, the network throughput of the two protocols is compared in a near-far scenario. An example of the near-far topology for six nodes, i.e., three concurrent communication links, is represented in Fig. 6. Again, the throughput of the (UWB)^2 protocol decreases with the number of concurrent links. On the other hand, the DCC-MAC protocol can cope with the increasing number of concurrent transmissions. Additional simulation results for DCC-MAC can be found in [2] for various scenarios.

5. CONCLUSION

We have discussed the management of impulsive interference in IR-UWB networks. We have shown that this kind of interference is an issue in IR-UWB and has therefore to be taken care of.

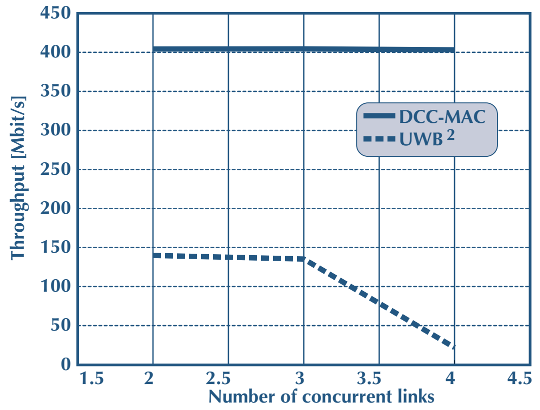

Figure 7: Performance of the DCC-MAC protocol and the $(UWB)^2$ protocol in a near-far scenario. The link distance is 10 meters. The throughput is plotted against the number of concurrent communication links. The transport protocol is UDP. The DCC-MAC protocol clearly outperforms the $(UWB)^2$ protocol. The $(UWB)^2$ protocol suffers from the contention on the common channel as well as the rate drop due to the RTS-CTS exchange.

We have further presented several techniques and proposals that address impulsive interference on the physical as well as on the link layer. Additionally, interference could also be managed on the network layer. There is already some work on routing protocols that try to route packets such that interference is limited. There are also other aspects that we have left out. We have not discussed the effect of these schemes on energy consumption. There is of course a tradeoff. A better system performance reduces the number of retransmissions and hence decreases the energy consumption. On the other hand, more complex transceiver designs increase the energy-consumption. Another important aspect of IR-UWB is its ranging capability. As for detection or channel estimation, interference will most probably matter, and some ways to deal with it will have to be considered.

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