MAC Design in Pulse-Based Communication Systems

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ABSTRACT

Pulse-based communication systems are a promising candidate in the deployment of future wireless networks, thanks to the potential robustness and capacity guaranteed by the transmission of pulses of very short duration. In the framework of pulse-based communication systems, the Impulse Radio-Ultra Wide Band (IR-UWB) technique recently received particular attention. In the past, most of the UWB research focused on hardware and physical layer aspects in order to solve the technological challenges posed by IR-UWB. UWB peculiar characteristics may, however, also stimulate innovative higher layers' design. This work addresses Medium Access Control (MAC) issues for IR-UWB communication systems and extends the discussion to wireless optical communication systems. Typical characteristics of an IR-UWB system are presented, and solutions proposed for such systems at the MAC layer are reviewed. The applicability of such solutions to an optical wireless communications system is then discussed, highlighting analogies and differences between IR-UWB and wireless optical systems.

1. INTRODUCTION

The design of a Communication System traditionally proceeds along the principle of a layered architecture. The aim is to design each layer of the system independently of the internal structure of the lower layers, which are considered as black boxes offering a service to upper layers [1].

Rules of interaction between different layers are defined by interfaces that determine the requested inputs and corresponding outputs. Within this framework, the MAC is generally considered as the bottom part of the Data Link Control (DLC) layer. The service offered by the MAC to the upper DLC is to provide a bit pipe, preventing or resolving contentions in the access to the medium. Following the layered approach, the functions executed in the MAC should be defined without taking into account the underlying physical layer. The design of an efficient MAC often requires however an accurate knowledge of the physical layer, and in most existing systems specific properties of the transmission technique are exploited in order to reduce the effect of multiple access interference. In the case of pulse-based systems, this is a crucial issue where the impulsive nature of the transmitted signal may enable the definition of novel MAC functions, as well as lead to a drastically different implementation of more traditional MAC functions.

This is the case for Impulse Radio Ultra Wide Band (IR-UWB) systems, where the use of very short (sub-nanosecond) pulses provides a high robustness to Multi User Interference, in particular in Low Data Rate (LDR) applications, and enables the adoption of a medium sharing approach based on Aloha, which is usually not suitable for traditional wireless systems due to the impact of packet collisions.

The Medium Access Control solutions proposed for low data rate IR-UWB systems are appealing for wireless optical systems, given the similarities between the two technologies: it is thus interesting to identify analogies and differences between wireless optical systems and IR-UWB, in order to evaluate to what extent solutions developed for IR-UWB can be applied to wireless optical systems.

The paper is organized as follows. Section 2 presents the signal format for an IR-UWB system, while Section 3 describes medium access in low data rate UWB systems. Finally, Section 4 analyzes differences and analogies between LDR IR-UWB systems and wireless optical systems, and discusses the applicability of medium access solutions designed for IR-UWB to wireless optical systems.

2. TIME HOPPING IMPULSE RADIO UWB SIGNALS

The UWB definition released by the FCC [2] does not limit the generation of UWB signals to impulse radio, and opens the way at least in the USA for alternative, i.e., non-impulsive schemes. An ultra wide bandwidth, say 500 MHz, might be produced by a very high data rate, independently of the characteristics of the pulses. The pulses might for example satisfy the Nyquist criterion at operating pulse rate $1/T$, which would require a minimum bandwidth of $B = 1/2T$, and thus be limited in frequency but unlimited in time having the classical raised-cosine infinity-bouncing shape with nulls at multiples of $1/T$. Systems with an ultra wide bandwidth of emission due to high speed data rate rather than pulse width, provided that the fractional bandwidth or minimum bandwidth requirements are verified at all times of the transmission, are not precluded. Methods such as for example orthogonal frequency division multiplexing (OFDM) and multi-carrier code division multiple access (MC-CDMA) are capable of generating UWB signals, at appropriate data rates. Commercial High Data Rate UWB products adopt indeed a multi-band alternative in which the overall available bandwidth is divided into sub-bands of at least 500 MHz. Nevertheless pulse-based UWB signals are the solution adopted for LDR UWB

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systems, thanks to the lower complexity guaranteed by this approach [3].

In the following we will focus on impulse radio UWB and specifically TH-UWB in which spectrum expansion is obtained by using very short pulses besides the spreading introduced by coding. RF modulation is rarely mentioned in UWB systems, which typically operate in the baseband. While RF modulation is obviously applicable to UWB as well, a shift in operating frequency can be potentially obtained here by pulse shaping.

Since modulation and multiple access are independent processes, TH-UWB may adopt in principle different schemes for data modulation, like PPM, PAM or OOK. A specific modulation scheme might be more appropriate for one or the other scheme, as a function of the resulting spectrum shape and characteristics.

We now focus on the generation process for a TH-UWB signal.

Suppose that binary data flows originate from N_u users with same bit rate $R_b = 1/T_b$, where T_b is the bit period. In order to avoid catastrophic collisions, each user is associated with a different TH code. The transmitted signal by the n-th user can be expressed as follows:

$$s_{TX}^{(n)}(t) = \sum_{j=-\infty}^{\infty} p(t - jT_s - c_j^{(n)}T_c - \varepsilon d_j^{(n)}) \tag{1}$$

where $p(t)$ is the impulse response of the pulse shaper. According to Eq. (1), the UWB signal consists of a train of pulses that are transmitted with an average repetition time T_s. The j-th pulse is further shifted by two additional amounts due to coding and modulation, as will be described below.

The $c_j^{(n)}T_c$ term represents the effect of the TH code, where $c_j^{(n)}$ is the j-th coefficient of the TH sequence assigned to the n-th user and T_c is the basic time-shift introduced by the TH code that is the chip time. A TH code is formed by a sequence of N_p independent and identically distributed random variables, all characterized by a probability $1/N_h$ to assume one of the integer values in the range $[0, N_h\text{-}1]$. Each TH code has same probability of being selected and is independent of all other codes.

The $\varepsilon\, d_j^{(n)}$ term represents the time-shift which is eventually introduced by the modulation, where ε is the PPM dither and $d_j^{(n)}$ is the binary value conveyed by the j-th pulse. In principle, one single pulse may be used to represent one bit. In order to improve system robustness, however, it is common sense to use more than one pulse for representing a bit. In the general case of N_s pulses per bit, the PPM scheme operates by shifting all N_s pulses corresponding to a 1-bit by ε. The signal format in Eq. (1) thus rewrites:

$$s_{TX}^{(n)}(t) = \sum_{j=-\infty}^{\infty} p(t - j \cdot T_s - c_j^{(n)} \cdot T_c - \varepsilon \cdot b_{\lfloor j/N_s \rfloor}^{(n)}) \tag{2}$$

where $\lfloor x \rfloor$ is the inferior integer part of x and $b_x^{(n)} = b^{(n)}(xT_b)$ is the x-th bit of the binary data flow of user n. We assume that all bits are independent and identically distributed random variables with equal probability of being 0 or 1.

In order to avoid both pulse overlapping and ambiguity between pulse positions, a few constraints must be introduced among signal parameters of Eq. (2), such as $T_s \le T_b / N_s$, $T_c \le T_s / N_h$ and $\varepsilon \le T_c - T_M$ where T_M represents the time duration of the single pulse $p(t)$.

3. MEDIUM ACCESS FOR LOW DATA RATE IR-UWB SYSTEMS

The high temporal resolution of IR-UWB signals has the beneficial side effect of reinforcing robustness to MUI, in particular for low data rate applications [4]. As a consequence, access to the medium in low data rate UWB networks can be based on a most straightforward solution, that is Aloha [5], [6]. The adoption of an Aloha-like approach may also favor lowering costs, given that it does not rely on specific PHY functions, such as Carrier Sensing, and may thus be adapted, with no significant effort, to different PHYs.

According to the Aloha principle, devices transmit in an uncoordinated fashion. Thanks to resilience to MUI offered by impulse radio, correct reception in the presence of multiple simultaneous links is possible.

As for the duty cycle of emitted signals, low data rate scenarios usually lead to an average Pulse Repetition Period (PRP), that is the average time between two consecutive pulses emitted by a device, in the order of $10^{-4}/10^{-5}$ s, with an average duration of emitted pulses typically in the order of 10^{-10} s. Theoretically, the duty cycle can thus be as low as 10^{-6}. A detailed analysis of this issue requires however introducing the channel model, in order to take into account propagation effects on pulse duration.

Furthermore, if Time Hopping (TH) is the selected coding technique, TH – Code Division Multiple Access (TH-CDMA) is a natural choice for multiple access. The adoption of TH-CDMA can introduce an additional degree of freedom, since the effect of pulse collisions is further reduced by the adoption of different codes on different links. Two factors cooperate in determining the robustness to MUI, that is low duty cycle of emitted signals and association of different TH-Codes to different links.

These considerations led to the Uncoordinated, Wireless, Baseborn protocol for UWB ($(UWB)^2$) MAC protocol, based on the combination of ALOHA with TH-CDMA [5]. $(UWB)^2$ 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. CDMA, in particular, is a well-known solution for designing multi-channel MAC protocols for wireless networks. A key issue in the application of CDMA strategy to ad hoc networks is the code assignment algorithm. As indicated in [7], possible code assignment strategies fall in one of the following categories: a) Common code scheme where all terminals share the same code, and code collisions are avoided thanks to phase shifts between different links, b) Receiver code scheme where each terminal has a unique code for receiving, and the transmitter uses the code of the intended receiver for transmitting a packet, 3) Transmitter code scheme where each terminal has a unique code for transmitting, and the receiver switches to the code of the transmitter for receiving a packet, and 4) Hybrid scheme, that is a combination of the previous schemes.

$(UWB)^2$ adopts a hybrid scheme, based on the combination of a Common code for signaling and Transmitter codes for data transfers. This solution has the advantage of allowing an increased multiple access capability if compared to the cases of Common and Receiver TH-Code, while still allowing a terminal to listen on a single TH code in the idle mode.

The performance of the $(UWB)^2$ protocol was evaluated by means of simulations, taking into account the impact of channel and Multi User Interference, by means of an accurate MUI model based on the concept of Pulse Collision [8]. Throughput and packet delay were analyzed as a function of channel characteristics, number of users and user data rates. Simulation results showed that in typical LDR scenarios, with rates from 10 kb/s to 100 kb/s and 10 to 100 users, the protocol provides high throughput and low delays and constitutes thus a viable solution for UWB low data rate networks [9].

4. EXTENSION TO WIRELESS OPTICAL SYSTEMS

Wireless indoor optical systems have usually been proposed as a solution for short distance, point to point connections. This choice was mainly due to the limitation imposed by the need of direct visibility between emitter and receiver that, combined with the limited field of view of optical transmitters and receivers, prevented from achieving broadcast transmissions, required for competing with radio wireless systems.

The availability of diffuse or quasi-diffuse wireless optical systems, involving a reflector that distributes the signal transmitted by each emitter, opens however the way to the adoption of wireless indoor optical systems as an alternative to radio systems, at least in specific application scenarios, where the peculiar characteristics of optical signals offer an advantage over radio systems [10], [11]. Optical systems present in fact advantages over radio systems under two main aspects:

- Security: the impossibility of communicating through obstacles that makes broadcast communications hard to achieve provides at the same time an appealing solution for security and privacy. Optical signals are in fact inherently confined to the intended operation environment, preventing malicious devices from obtaining sensible information (for example biomedical data);
- Compatibility: the use of optical frequencies allows the operation of optical communication systems in scenarios where radio communications are impossible or forbidden (industrial environments with machinery causing strong interference at radio frequencies, or medical environments with devices sensible to the emissions of radio systems).

In scenarios where such properties become relevant diffuse optical systems can thus play an important role. In order to make the wireless optical solution viable, however, it is paramount to define efficient medium access strategies that take into account the specific characteristics of the transmitted signal. In this view, the analogies between optical systems and pulse-based UWB systems suggest that the solutions proposed for medium access in IR-UWB could be adopted with valid results in optical wireless systems as well. IR-UWB and indoor optical wireless systems share in fact the following characteristics:

- Signal spreading achieved by means of short pulses: the adoption in both systems of short pulses makes the analysis on the impact of pulse collisions carried out for IR-UWB directly applicable to optical wireless signals, since in both systems pulses with sub-nanosecond duration can be adopted, thus providing a high processing gain.
- Modulation and coding technique: non-coherent modulation schemes (such as PPM or OOK) typically proposed for LDR UWB systems are also the typical solution in optical wireless systems, where Intensity Modulation with Direct Detection is adopted.

Such common characteristics between IR-UWB and optical systems indicate that the multi-channel Aloha approach adopted in the $(UWB)^2$ protocol for IR-UWB systems could lead to comparable results in diffuse optical systems, thus providing an alternative to existing proposals for multiple access in such systems, such as orthogonal optical codes, in particular for LDR applications.

5. CONCLUSIONS

In this paper we presented the characteristics of a typical IR-UWB LDR system, reviewing the format of the transmitted signal and describing a solution for medium access that takes into account the specific characteristics of an IR-UWB signal using Time Hopping.

The similarities between IR-UWB signals and diffuse wireless optical systems suggest that the medium access protocol $(UWB)^2$, originally proposed for LDR UWB systems, can be an interesting solution for access in diffuse optical systems as well, taking advantage of the impulsive nature of the transmitted signal in order to provide a simple and robust solution for medium access.

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