Combining Wireless Optical and UWB for low data rate applications

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Abstract

Recent developments in the field of Ultra Wide Band (UWB) radio and networks led to the definition of a new Impulse Radio (IR) UWB-based IEEE standard for low data rate communications, named IEEE 802.15.4a. A typical feature of UWB radio is a large bandwidth together with limited available emission power, as set by regulatory bodies. UWB communications may, therefore, be severely affected by external interference.

IR-UWB and Diffuse Wireless Optical (DWO) signals share a major feature of being impulsive in nature; we suggest that the combination of these two technologies may bring benefits, and overcome limitations. To this aim, we propose a strategy for combining these two physical layers by adopting a common Medium Access Control (MAC) protocol, based on selecting the most suitable physical layer as a function of external interference. Results obtained by simulation for different patterns of external interference indicate that system performance may be strongly improved by the proposed IR-DWO combination strategy.

Keywords: Wireless, UWB, Medium Access Control.

1. Introduction

Low data rate communications for sensor and ad-hoc networks have been addressed by recent standards for low rate, low complexity, and low power wireless networks. In particular, the IEEE 802.15.4 standard, see ZigBee [1], was recently revisited into version 802.15.4a, that incorporates ranging and positioning. This version of the standard adopts Impulse Radio Ultra Wide Band (IR-UWB) as a possible transmission technique for both indoor and outdoor communications [2]. Attractive features of IR-UWB that led to its selection for the standard were, among others, the inherent high temporal resolution that allows accurate ranging while providing robustness to multipath, and reliable communication despite Non-Line-Of-Sight (NLOS) propagation conditions [3]. As well known, UWB radio frequencies of operation may overlap with other radio services, and therefore transmissions are severely power limited. As a drawback, UWB links may suffer from narrowband interference [4], [5]. This is particularly true when interferers are inherently present, as in medical premises where diagnostic machines emit RF radiations while operating, as well as in industrial environments. In these cases, network performance was shown to improve significantly by using Diffuse Wireless Optical (DWO) [6].

DWO has been proposed in the past for indoor applications, as a complementary solution to the Radio Frequency (RF) technology. As pointed out in [7], DWO is best suited for low-to medium bit rates, since multipath propagation caused by reflection of transmitted signals over walls, floor, and ceiling may generate severe intersymbol interference. In addition, distances of propagation are limited by a large path loss associated with multiple reflections [8]. Achievable rates are in the order of 1 Mb/s over a few meters. In order to achieve higher bit rates (tens of Mb/s and above) the use of a multibeam transmitter combined with a receiver adopting several receiving elements was proposed in [9]. This allows to reach bit rates in the order of 100 Mb/s. When space-time coding is adopted, rates can hit hundreds of Mb/s [10].

The idea of combining DWO and RF links was proposed in the past, see [11], where mobile nodes carrying 802.11 RF and LOS optical interfaces were coordinated at the routing layer, i.e. packets coming from the two network interfaces were routed according to predefined routing tables.

The approach proposed in this paper differs from previous work as we propose to move the coordination between two physical layers up to the MAC layer, where the best physical layer is selected according to environmental conditions. IR and DWO signals share a major feature, i.e. they are impulsive in nature, suggesting the possibility of adopting a same MAC, leading to convergence of IR-UWB and DWO.

The paper is organized as follows. Section 2 describes the MAC, $(UWB)^2$, originally proposed for low data rate UWB networks, and its application to low data rate DWO networks, as well as introducing the proposed physical layer selection strategy. System simulation and discussion of results are reported in Section 3.

2. The MAC strategy and the IR vs. DWO selection strategy

Access to the medium in low data rate UWB networks can be based on a most straightforward solution, i.e. Aloha ([12], [13]), by which devices transmit in an uncoordinated fashion. Thanks to resilience to MUI, as offered by impulse radio, correct reception for multiple simultaneous links can be obtained. An Aloha-like approach may also favor lowering costs, since it does not rely on specific physical layer (PHY) functions, such as carrier sensing, and may thus be adapted with little effort to different PHYs. As for the duty cycle of emitted signals, low data rate scenarios usually lead to an average Pulse Repetition Period (PRP), i.e. the average time between two consecutive pulses emitted by a single device, on the order of $10^{-4} \div 10^{-5}$ s, with an average duration of emitted pulses typically on the order of 10^{-10} s. In principle, the duty cycle can thus be as low as 10^{-6}. A careful analysis of this issue would require, however, to incorporate the effect of the channel on pulse duration.

$(UWB)^2$ is a multi-channel MAC protocol that is suitable for the case under examination; it is based on the combination of Aloha with TH-CDMA [14]. When Time Hopping (TH) is the adopted coding method, TH-CDMA is a natural choice for multiple access, with the beneficial effect that the probability of pulse collision is further reduced by associating different codes to different communication links. The selection of the physical layer is carried out according to the following strategy:

$$\text{Evaluate } C = C_{UWB} \cdot BER_{UWB} - C_{DWO} \cdot BER_{DWO} \Rightarrow \begin{cases} \text{if } C > 0 & \text{select} \quad \text{DWO} \\ \text{if } C < 0 & \text{select} \quad \text{UWB} \end{cases} \tag{1}$$

where BER_{UWB} is the bit error rate measured on the UWB physical layer, BER_{DWO} is the bit error rate measured on the DWO physical layer, C_{UWB} and C_{DWO} are two cost coefficients to be defined according to the selected performance goal. BER_{UWB} and BER_{DWO} can be measured either on the basis of previous data packet exchange, or by means of beacon packets sent on the two physical layer interfaces. Two possible performance goals that can be considered in the definition of the cost coefficients are straightforward BER minimization vs. energy consumption minimization. In the former case, the two coefficients can be both set to 1, leading at any time to the selection of the physical layer that achieves the lowest BER; in the latter case the two cost coefficients should be defined according to the relative cost for each transmitted bit in terms of energy. In the following we will consider the case of BER minimization, and set $C_{UWB}=C_{DWO}=1$.

3. Simulation and discussion

A room 12m x 12 m (indoor) where 10 devices were randomly deployed was simulated. Each device was simulated with an 802.15.4a-like UWB module and a DWO physical layer composed of a LED diode for transmission and a PIN for reception. User bit rate R was 10 kb/s. Transmission rate was 966 kb/s.

The UWB channel was modeled as indoor Line Of Sight (LOS) and Non-Line Of Sight (NLOS) according to the 802.15.4aTG channel models CM1 and CM2 [15]. The UWB physical layer settings were derived from [2], and can be summarized as follows: IR-UWB with a band of 494 MHz centered at 3952 MHz (corresponding to Channel 2 of the 802.15.4a channel scheme); Average Pulse Repetition Frequency (PRF): 2.895 MHz; 3 Pulses Per Symbol (N_s); PPM modulation; transmission power P_{TX} fixed to FCC indoor limit [16], leading for the considered bandwidth to P_{TX} = 36.6 μW; TH-coding with pseudorandom codes. Multi-user interference was modeled according to the Pulse Collision model [17]. The narrowband interference (NBI) was modeled as an additive white Gaussian noise [18].

DWO links were On-Off Keying (OOK) modulated. Performance was estimated based on the quantum limit, by which error probability for OOK optical links is given by [19]:

$$P_e = 0.5 \cdot p(0/1) = 0.5 \cdot e^{-\Lambda} \tag{2}$$

where p(0/1) is the probability of deciding for a 0 when a 1 is transmitted, and $\Lambda = E_b / (hf)$ is the received symbol energy per energy of a single photon. As stated, the quantum limit assumes that p(1/0)=0. This limitation was overcome in order to account for multiuser interference, that is:

$$P_e = 0.5 \cdot p(0/1) + 0.5 \cdot p(1/0) = \\ = 0.5 \cdot \left[e^{-\left(\frac{E_b + 0.5 \cdot \sum_{i=1}^{N_{int}} E_i}{hf} \right)} + \left(1 - e^{-\left(\frac{0.5 \cdot \sum_{i=1}^{N_{int}} E_i}{hf} \right)} \right) \right] \quad (3)$$

where N_{int} is the number of interferers transmitting during a symbol time and E_i is the energy received at the reference receiver due to the transmission of the i-th interferer. Symbols 0 and 1 are equiprobable. E_i and E_b are determined by the path loss between each transmitter and the reference receiver. Such path loss was evaluated according to the model proposed in [20] for LOS and NLOS scenarios.

Figure 1 shows that DWO throughput increases as a function of the transmitted optical power, and will eventually saturate, due to the increasing preponderance of MUI (see Eq.3). Figure 2 shows the UWB throughput obtained in similar conditions, as a function of power spectral density N_{NBI} of the Gaussian noise modeling the NBI.

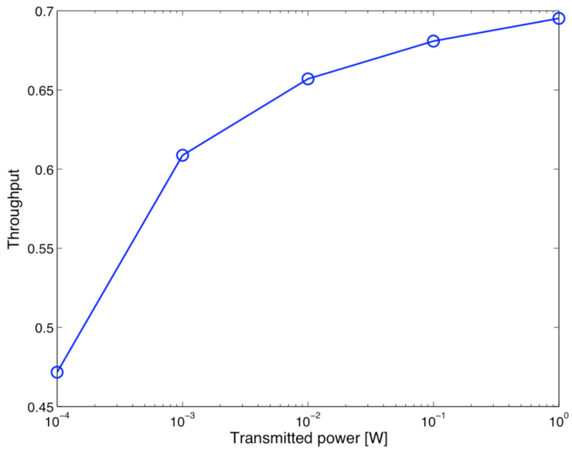

Figure 1. Throughput in the case of DWO physical layer for a network of 10 nodes as a function of the transmitted optical power.

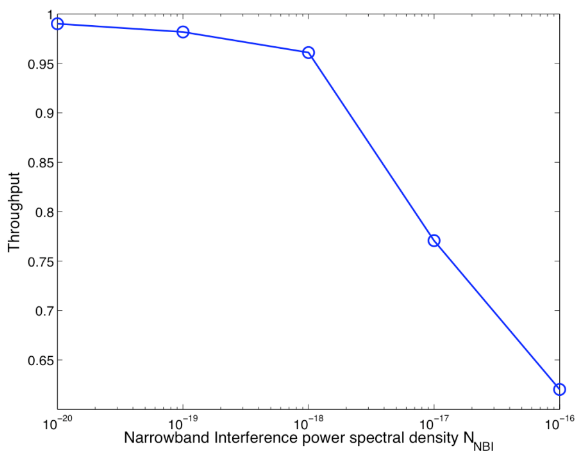

Figure 2. Throughput in the case of UWB physical layer for a network of 10 nodes as a function of the power spectral density of a narrowband interferer N_{NBI}.

Note that the presence of NBI may severely reduce UWB performance, leading to lower throughput values than DWO. The adoption of the physical layer selection strategy may therefore improve overall network performance by achieving at all times the minimum possible BER, and thus the best possible throughput.

In conclusion, we investigated the possibility of combining two different impulse-based technologies i.e. UWB and optical wireless, for application to low data rate wireless networks with external radio interference (e.g. industrial settings) and/or severe limitations on the allowed amount of emitted radiations (e.g. medical premises). A strategy for selecting the best technology according to the external environment conditions, that operates on the basis of BER measurements, was proposed. Results obtained by simulation show that the proposed method may lead to overall performance improvement.

4. References

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