UWB Network Coexistence and Coordination: a Cognitive Approach

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***Abstract*— Introducing cognitive features in the design of wireless networks may have beneficial effects on network coexistence and coordination. In this paper, the performance of an Impulse Radio UWB network composed of IEEE 802.15.4a-like devices is considered in different coexistence environments with and without the presence of cognitive mechanisms. A novel coding technique, named Fluid Coding, that is suitable to cognitive implementation, is investigated. Results obtained by system simulation indicate that cognitive rules are essential to allow wireless communications towards a reliable coexistence regime.**

I. Introduction

Cognitive radio is an innovative concept based on the idea of a radio device that is aware of the scenario in which it operates, and thus capable to adapt its behaviour to the changes of the operating environment. Cognitive features are particularly attractive in those scenarios where devices must cope with interference, and in particular when different wireless networks must share the same radio resource and therefore interfere with one other during operation. In this framework, a new income network may become active at any time, causing thus a global perturbation over the quality of already established wireless links. One of the major challenges is therefore to find a way for controlling inter-system interference under the above unpredictable radio environment; a network that was aware of the surrounding environment could adapt its parameters and transmission features dynamically, providing an efficient spectrum usage together with the possibility of facing unexpected changes and of meeting, if necessary, emission masks and quality of service requirements.

The coexistence principle is intrinsic to UWB networks, since UWB radio signals overlap in frequency with a variety of other narrowband and wideband radio signals. UWB radio signals are in fact characterized by a very large bandwidth, spanning from 500 MHz to a few GHz. The analysis of UWB networks is thus a perfect study case for investigating the effects of introducing cognitive mechanisms in the design. The object of this paper is to study the effect of a cognitive approach in low data rate Impulse Radio Ultra Wide Band (IR-UWB) self-organizing networks. Cognition is introduced by making a reference network capable of sensing the radio environment and selecting accordingly, among a set of several, an optimal pulse waveform that minimizes its perceived interference cost. In addition cognition is also implemented by appropriate coding using a novel coding technique named Fluid Coding that is used by the network to control interference.

The paper is organized as follows. Section 2 introduces the signal format. Section 3 explaines the adopted cognitive model. Section 4 describes simulation settings and results for the adopted cognitive model. Section 5 describes the new coding technique and provides related simulation results. Section 6 concludes the paper.

II. Signal Format

The considered UWB signal format has the typical expression of Impulse Radio (IR) signals, with Time-Hopping coding (TH) and binary Pulse Position Modulation (PPM). The reference transmitter TX transmits a signal s(t) described by the following expression:

$$s(t) = \sqrt{P_{TX}\, T_s} \sum_j p_w(t - jT_s - c_j\, T_c - a_j\, \epsilon), \quad (1)$$

where P_{TX} is the average transmitted power, T_s is the pulse repetition period, $p_w(t)$ is the energy-normalized pulse shape, T_c represents the discrete chip time value, c_j is an integer value upper bounded by the cardinality of the code, a_j is the data symbol carried by pulse j, and ϵ is the PPM shift. Note that the bit interval T_b is: $T_b = N_s\, T_s$, where N_s is the number of transmitted pulses per bit. Transmission power P_{TX} is upper bounded by a specified maximum power level, indicated as P_{MAX}, which takes into account technological limitation or regulatory recommendations, as for example the UWB emission masks provided by the Federal Communications Commission (FCC). The expression of $s(t)$, represented in Eq. 1, shows that it is possible to change the spectral characteristics of the UWB signal by selecting different pulse waveforms, that is different pulse shapes $p_w(t)$, in order to face more efficiently the varying interference scenario.

A general flat Additive White Gaussian Noise (AWGN) channel model is assumed. If external interference and Multi User Interference (MUI) are both present, the signal $r(t)$ at the input of a reference receiver RX writes as in Eq. 2:

$$r(t) = \sqrt{P_{RX}\, T_s} \sum_j p_w(t - jT_s - c_j\, T_c - a_j\, \epsilon - \tau) + \eta_e(t) + \eta_{mui}(t), \quad (2)$$

where P_{RX} is the average received power after propagation over the link between TX and RX, τ is the propagation delay, $\eta_e(t)$ accounts for thermal noise and external interference provoked by wireless devices that operate outside the network (including an external UWB network), and $\eta_{mui}(t)$ represents MUI contribution (deriving from devices belonging to the network).
At receiver side a coherent correlator followed by a Maximum Likelihood detector is adopted. Soft decision detection is performed, so that the decision variable $Z(x)$ that is present at the correlator output after the x_{th} bit interval is given by Eq. 3 [1]:

$$Z(x) = Z_u + Z_e + Z_{mui}, \tag{3}$$

where Z_u, Z_e, and Z_{mui} are the useful contribution, the external noise contribution, and the MUI contribution, respectively. System performance can be expressed in terms of the signal to noise ratio SNR measured at the correlator output, which is defined in Eq. 4:

$$SNR = \frac{E_u}{\eta_e + \eta_{mui}}, \tag{4}$$

where E_u is the received useful energy per bit for the reference link, η_e is the variance of the Z_e contribution, and η_{mui} is the variance of the Z_{mui} contribution introduced by the other active nodes.

III. Network Architecture and Cognitive Model

We suppose that all the nodes in the network are able to communicate through one elected node, denoted as the Conscious Node of the network (CNode). Network architecture is therefore centralized in the CNode, that implements the cognitive paradigm and plays the role of network coordinator. Time Hopping (TH) coding is used for discriminating among users, according to a method that is commonly indicated as TH Impulse Radio (TH-IR). Data exchange between the CNode and any other node requires the set-up of a specific communication channel that is identified by a dedicated TH code. The performance of a given link between one active node and the CNode is expressed by Eq. 4, where one can substitute [2]:

$$Eu = (N_s)^2 \, P_{RX} \, T_s,$$

$$\eta_e = N_s \, \eta_p(w),$$

$$\eta_{mui} = (N-1) \, N_s \, \sigma_m^2(w) \, P_{RX},$$

where $\eta_p(w)$ is the variance of noise collected for one single pulse, N is the number of active nodes in the network, and $\sigma_m^2(w)$ is a MUI weight defined as:

$$\sigma_m^2(w) = \int \left[\int p_w(t+z)[p_w(t) - p_w(t-\epsilon)]dt \right]^2 dz. \tag{5}$$

We can therefore rewrite Eq. 4 as:

$$SNR = \frac{1}{R_b} \frac{P_{RX}}{\eta_p(w) + \sigma_m^2(w)\,(N-1)\,P_{RX}}, \tag{6}$$

where $R_b = 1/T_b$. Under the assumption that both $\eta_e(t)$ and $\eta_{mui}(t)$ can be modelled as white Gaussian random processes, one has:

$$BER = \frac{1}{2} \, erfc \left(\sqrt{\frac{SNR}{2}} \right). \tag{7}$$

The SNR expressed in Eq. 6 provides an indication of the link quality when noise and MUI are both present. A prerequisite for correct detection of transmitted data, however, is the synchronization between TX and RX. For fixed length of the synchronization trailer, performance of the synchronization procedure depends on the signal to noise ratio measured on the single pulse SNR_p. If SNR_p is at least equal to a minimum threshold value SNR_0, which measures the sensitivity of the receiver with respect to synchronization, a link between TX and RX can be established. The expression of SNR_p can be derived from Eq. 6 by substituting $R_b = 1/T_s$. The CNode can thus support N active connections with N nodes in the network provided that:

$$SNR = \frac{T_s \, P_{RX}}{\eta_p(w) + \sigma_m^2(w)\,(N-1)\,P_{RX}} \geq SNR_0. \tag{8}$$

Note that in Eqs. 6 and 8 both synchronization performance and the quality of the uplink connections depend on the waveform $p_w(t)$ that is adopted for transmission. In [3] and [8] a full characterization of the adopted traffic model is described in detail. All devices communicate by exchanging data with the CNode, which routes data to other nodes that are located inside its coverage area. As proposed in [3], network dynamics can, in the present case, be well described by the hybrid system formalism [5]. We assume that the CNode has the capability of continuously sensing its surrounding environment and of determining the noise floor perceived by its receiver. Based on environment sensing, the CNode estimates the values of $\eta_p(w)$ and $\sigma_m^2(w)$ and then computes the value of minimum power $P_{min}(w)$ that must be received from each node in order to guarantee for each connection the condition:

$$P_{min}(w) = \frac{\eta_p(w)}{T_s} \left(\frac{1}{SNR_0} \frac{\sigma_m^2(w)\,(N-1)}{T_s} \right). \tag{9}$$

If a set of K different waveforms is available at physical layer, the CNode can use Eq. 9 to determine the waveform that better adapts to the environment, i.e. the one that leads to the smallest $P_{min}(w)$ value, for $w = 1, \ldots, K$. The CNode can thus determine the waveform $p_w^*(t)$ to be currently used by nodes and the corresponding $P_{min}(w^*)$. This message is broadcasted by means of a specific broadcast control channel. Each active node receives the information (sent using a known power level) and estimates the attenuation A_j characterizing its path to the CNode. Each node can therefore select the waveform w^* and adjust transmission power to $P_{TX_j} = A_j \, P_{min}(w^*)$ [4].

IV. Simulation Scenarios

In order to evaluate the impact of cognition on the considered UWB network performance, we have selected two different scenarios: in the first one the reference UWB network must coexist with several narrowband interferers, in the second

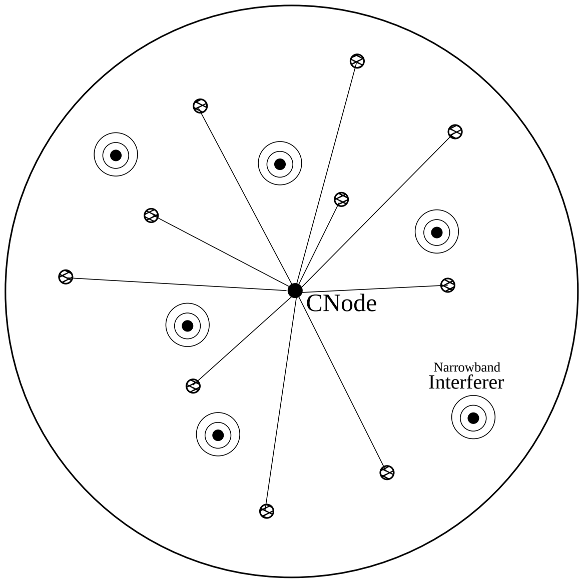

Fig. 1. The reference network, centralized in the CNode, faces the interference caused by narrowband transmitters become active in the area.

a different kind of interference, produced by an additional UWB network become active in the area, is taken into account. For both scenarios the considered reference network consists of one CNode located at the centre of a circular area with radius $R = 10\,m$. The area contains $N = 10$ active nodes. The active users are continuosly transmitting data towards the CNode during the whole duration of the simulation. At time t, the j_{th} active node ($j = 1, \ldots, N$) is transmitting a UWB signal with power $P_j(t) = A_j(t)\,P_{min}(t)$, where $P_{min}(t)$ and $A_j(t)$ are the requested power at the CNode to grant the target synchronization performance and the attenuation of the j_{th} uplink at time t, respectively. At time t the N active nodes adopt the waveform $p_w(t)$. Such waveform is determined by the CNode based on the evaluation process that has been previously described and can be selected among a set of K different waveforms $p_1(t), \ldots, p_K(t)$, represented by the first six odd derivatives of the Gaussian pulse. Waveform selection is performed based on the analysis of the external environment [6]. Specifically, we assume that the CNode may order a change in the adopted waveform only at multiples of a given interval, which accounts for the time that is required by each active node for modifying the characteristics of the pulse shaper. The number of active users in the reference network doesn't change during the simulation time.

A. Narrowband Interference Case

We assume that N_i narrowband interferers are present in the area, divided in N_a active interferers and N_s silent interferers. Figure 1 shows the considered situation. Unlike the active nodes, interfering devices do not transmit continuously. At each instant of simulation, each interfering device can assume one of two possible states: *active*, that is, the device is transmitting with a given power, bandwidth, and frequency of operation or *silent*, that is, the device is not generating any signal that is perceivable by the CNode. Transition from one state to the other is random; each device *j* is associated in fact with two fixed transition probabilities P_{A_j} and P_{S_j}, where P_{A_j} indicates the probability to move from silent to active, and P_{S_j} indicates the probability to move from active to silent. In the proposed simulation, changes in the state of the interfering devices are determined periodically, with a fixed period. At each multiple of the period duration, the jth interfering device switches-on with probability P_{A_j} if it was silent, or switches-off with probability P_{S_j} if it was active. In order to stress the CNode with continuous changes in the interference pattern, we modify the position of an interfering device every time it switches from silent to active.In order to highlight the effect of cognition on network coexistence, we consider, for each simulation, three different CNodes, whose performance will be compared in terms of number of allowed interfering links:

1) Smart CNode: The Smart Cnode is always capable to quantify the levels of interference associated to the K available waveforms that are measured at the receiver. The CNode is thus always capable of selecting the pulse shape that minimizes the value of $P_{min}(t)$, and, therefore, the waveform that minimizes transmission power for the active nodes of the reference network.

2) Amateur CNode: The Amateur Cnode is always capable to quantify the levels of interference that is measured at the receiver in correspondence of a sub-set of the K available waveforms. This sub-set consists of the last used waveform and the two adjacent waveforms. Within this subset the Amateur CNode is always capable of selecting the pulse shape that minimizes the value of $P_{min}(t)$.

3) Adaptive CNode: The Adaptive CNode initially selects a waveform $p_m(t)$ and does not perform any further selection of the pulse shape during network lifetime. However, the CNode quantifies the amount of received power $P_{min}(t)$ that is required from active nodes, but does not make any effort in optimizing transmission parameters based on the interference pattern. In this case, the CNode is adaptive but not cognitive. In fact the Adaptive CNode is not aware of the surrounding environment, and does not select among several strategies to improve the reference network performance.

B. UWB Interference Case

1) The Interfering Network: The considered UWB interfering network consists of one MNode located at the centre of a circular area with radius $R = 10\,m$. The network can activate up to $M = 49$ interfering links, one at a time, if permission is granted by the CNode operating in the reference network. All the devices belonging to the interfering network use the same pulse shape during the simulation time. The MNode is not provided with cognitive capabilities and is not aware of the surrounding radio environment. However the Mnode is able to listen to the CNode if required. The activation of the interfering links, when allowed by the CNode, doesn't follow any particular order and each device of the interfering network has the same probability to be selected.

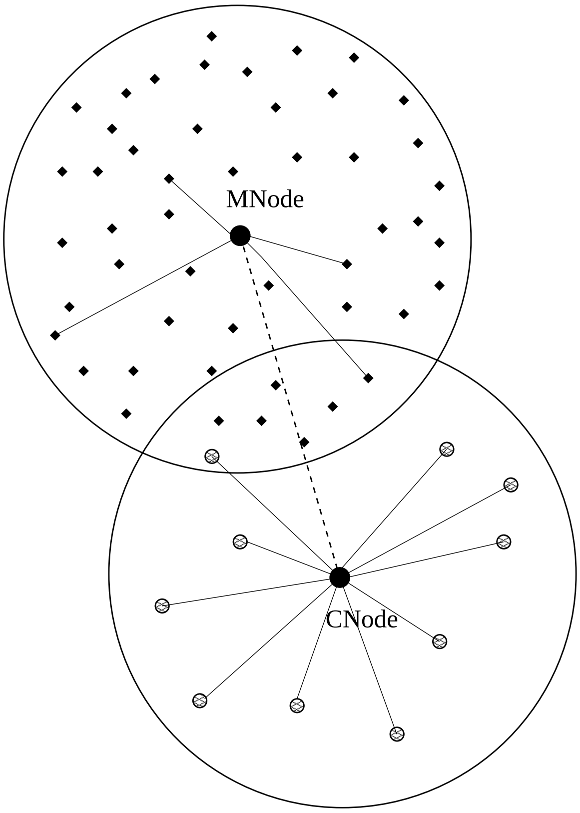

Fig. 2. The reference network, centralized in the CNode, faces the interference caused by a second UWB network, centralized in the MNode, become active in the area. The MNode is able to listen to the CNode.

The activation procedure is performed sequentially, every time-period τ, where τ is supposed to represent a sufficiently large amount of time to allow the active nodes of the reference network to modify the pulse shaper settings and to allow the CNode to perform the evaluation of the required minimum power.

2) CNode and MNode: The CNode evaluates the power P_{min} that is necessary to meet the requirements in terms of synchronization performance. We assume that, when the interfering network is not present, in other words when none of the potential interfering links is activated, the required power is smaller than the threshold $P_{min_{max}}$ that upperbounds it. When the MNode starts activating the interfering links one after another, the required P_{min} at the CNode becomes higher and can exceed the threshold. If that happens, the CNode stops the activation process and forces the MNode to release the newborn interfering links.
In order to highlight the effect of cognition on network coexistence, we consider, for each simulation, two different CNodes, the Smart Cnode and the Adaptive CNode previously defined, whose performance will be compared in terms of number of allowed interfering links:
Figure 2 provides an example of the considered scenario.

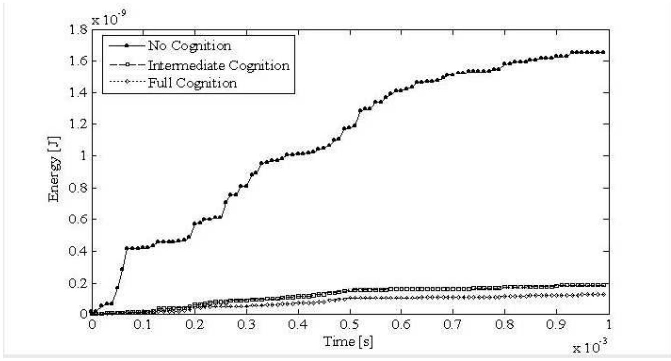

Fig. 3. Energy consumed by the reference active node expressed as a function of time for the three strategies under examination in the narrowband interference case.

V. Simulation Results

A. Narrowband Interference Case

Figure 3 is displays the energy values required to meet the synchronization threshold in the narrowband interference case for the three different levels of cognition at the CNode. As expected, the energy values that correspond to no cognition (black circles) are always higher than those obtained by introducing cognition in the network. Specifically, simulation of case A indicates that the reference node with full cognition has consumed at the end of the simulation period an amount of energy which is only the 9.25% of that consumed with no cognition. Similar results are observed for intermediate cognition: this option requires an amount of energy that is only the 12.34% of that measured with no cognition. Interestingly, energy consumption with intermediate cognition is proximal to that of full cognition. This result indicates that a significant increase in network lifetime may be achieved even by adopting sub-optimal algorithms with moderate complexity, provided that the rules of operation are adjusted in some extent to the state of the external environment.

B. UWB Interference Case

In Figure 4 the evolution of the number of allowed interfering links as a function of time is shown in detail. Every τ the MNode tries to activate a link; while the Smart CNode is able to manage the interference produced by all the 49 possible interferers, the Adaptive CNode can allow at most 32 interfering links to be able to meet the synchronization requirements in compliance with the power threshold Pminmax. For this first set of simulations the distance d between the CNodes and the MNode has been set to $10\,m$, the interfering devices are characterized by an emitted power of $10^{-4}\,W$, while the synchronization threshold is $SNR_0 = 4\,dB$. Figure 5 displays the average number of interfering links allowed by the Adaptive CNode and by the Smart CNode when the value of the synchronization threshold is varying. For this second set of simulations the emitted power of the interfering devices is equal to $10^{-3}\,W$ and the distance between CNode and MNode is d = 7 m. For the considered simulation scenario if the requested synchronization performance is represented by a threshold value up to $5\,dB$, the Smart CNode is able to allow all the possible interfering links of the second network, while the Adaptive CNode can sustain at most the interference produced by 13 interfering links. For higher values of SNR_0 the number of allowed links decreases for both the CNode typologies, but while the Smart Cnode is capable of allowing 11 interfering links when the threshold value is the highest considered, the Adaptive Cnode can accept only 1.3 on average. The Smart CNode performance appears particularly signicant if one consider that in this case the two networks are remarkably close to each other and that the interfering devices are characterized by an elevated emitted power. In Figure 6 the average number of interfering links allowed by the Adaptive CNode and by the Smart CNode is represented when only the distance d between the CNode and the MNode is varying. For this third set of simulations the synchronization threshold value has been set to $SNR_0 = 6\,dB$ and the emitted power characterizing the interfering devices has been kept equal to $10^{-3}\,W$. Note that even when the CNode and MNode are very close to each other, the Smart Cnode, that always chooses the best pulse shape depending on the surrounding radio environment, is able to allow up to 22 interfering links.

VI. FLUID CODING

The signal format considered so far and described by Eq. 1, is characterized by a conventional Time-Hopping coding, with a discrete chip time value T_c. When the discrete-valued $c_j\,T_c$ term is replaced by a real value c_j, coding shifts from standard to fluid and one can write:

$$s(t) = \sqrt{P_{TX}\,T_s}\,\sum_j p_w(t - jT_s - c_j - a_j\,\epsilon). \qquad (10)$$

When Fluid Coding is used, the transmitted pulse is no more bounded by the limited set of possible positions imposed by

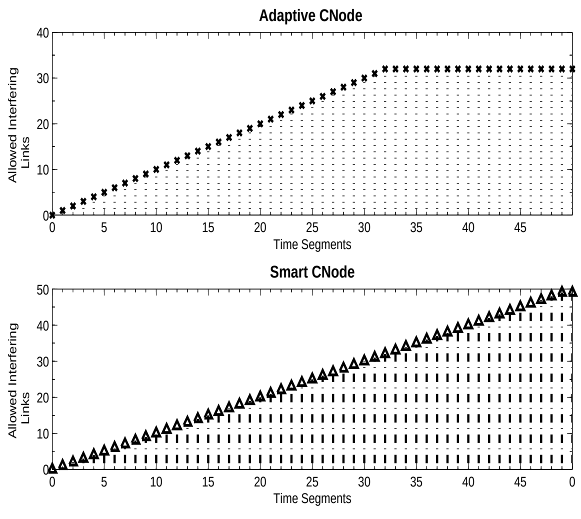

Fig. 4. Number of interfering links allowed by the Adaptive CNode and the Smart Cnode for each time segment, when operating in scenario 1 .

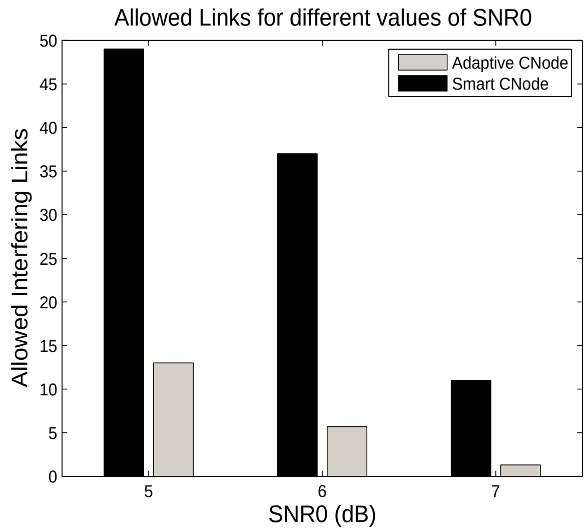

Fig. 5. Number of interfering links allowed by the Adaptive CNode and by the Smart CNode for different values of the synchronization threshold SNR_0.

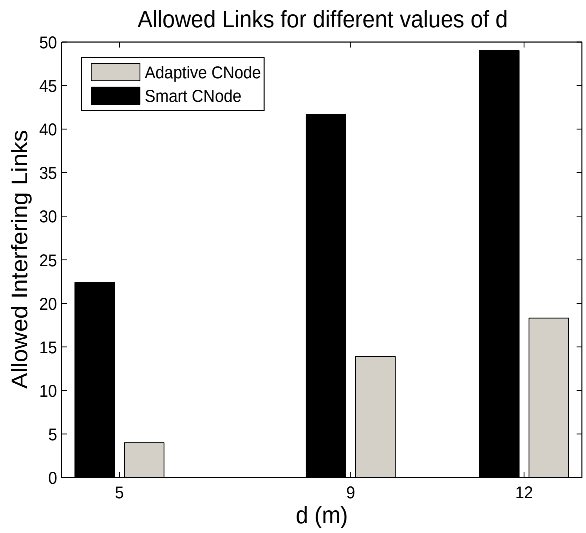

Fig. 6. Number of interfering links allowed by the Adaptive CNode and by the Smart CNode for different values of distance d between the CNode and the MNode.

the conventional Time-Hopping approach and this can lead to significant performance improvements if conveniently applied to spectrum shaping and MUI [7]. From a cognitive radio perspective, some key parameters of the code, such as the code period N_p, can be properly driven in order to mitigate interference and favour network coexistence.

The generation of the fluid code can be obtained by sampling a chosen analog waveform, for example a simple sinusoidal waveform, as shown in Figure 7 The generic element c_j of

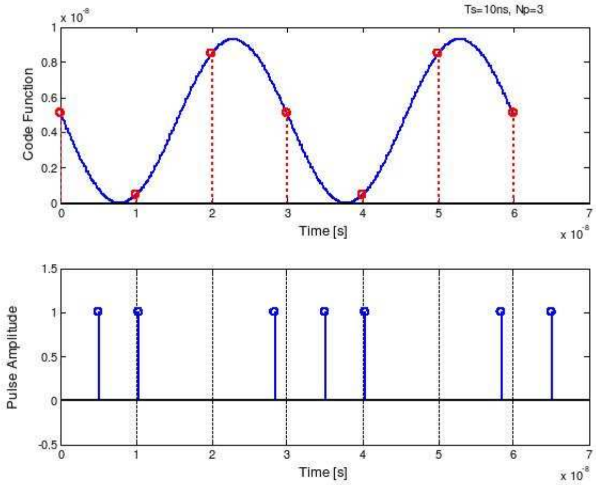

Fig. 7. Fluid Coding obtained sampling a sinusoidal waveform.

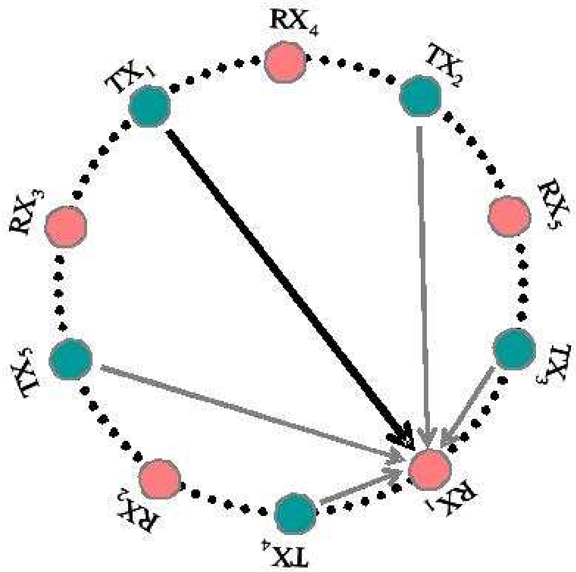

Fig. 8. Ring topology including 10 nodes: nodes are alternately transmitters and receivers. Each transmitter is associated to the receiver diametrically opposed.

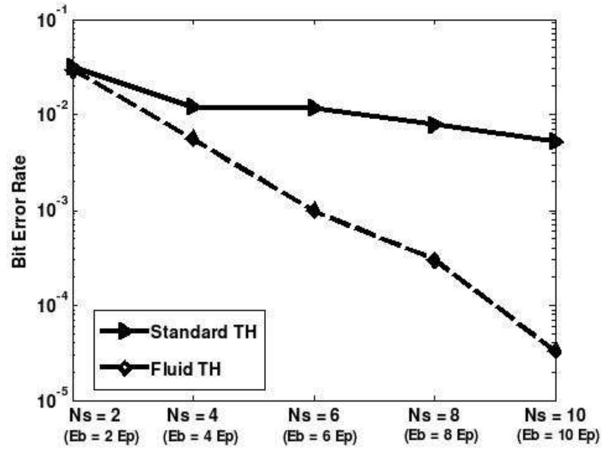

Fig. 9. BER in the two cases of standard TH coding (full line and triangles) and Fluid TH coding (dotted line and losangues) for the considered ring topology (radius = 10 m and 10 nodes) for different values of the number of pulses per bit Ns. The corresponding transmitted energy per bit E_b is also indicated for convinience as a multiple of the energy per pulse $E_p = 1.49 \cdot 10^{-18}$ Joule .

the code in the sinewave case is expressed by:

$$\begin{aligned} c_j = c(jT_s) &= \frac{(T_s - T_m - \epsilon)}{2}\left(1 + sin(2\pi\, f_0 j T_s + \phi)\right) \\ &= \frac{(T_s - T_m - \epsilon)}{2}\left(1 + sin(2\pi\frac{j}{2N_p} + \phi)\right). \end{aligned} \tag{11}$$

Note that in case of multi-user communications each user can be assigned with different f_0 or ϕ values to obtain mutual interference mitigation.

In order to test the beneficial effect of Fluid Coding we have considered a ring topology composed of 10 nodes (5 transmitters and 5 receivers). The nodes forming the ring represent alternately a receiver and a transmitter; each transmitter is associated to the diametrically opposed receiver. In this way, each receiver is put in a critical situation with respect to received useful power and also from a Multi User Interference point of view related to the presence of dominant interferers. Figure 8 displays the described topology. Simulation results provided by Figure 9 offer a performance comparison between standard Time-Hopping coding and Fluid Coding when different values of the number of pulses per bit N_s are taken into account. Note that increasing the number of pulses per bit results in a decreased bit rate and in an increased energy transmitted per bit. The Signal to Interference Ratio (SIR) also increases when Ns increases; in fact, when SIR is evaluated, the useful contribution rises in a quadratic way with respect to Ns, while the interfering contribution rises in a linear way. Fluid Coding can successfully be applied in a variety of frameworks. For instance in an uncoordinated and asynchronous network, clustering could be easily achieved by separating different clusters with different periods of the sinusoidal fluid TH code. In this way, interference among different subgroups would be better controlled, and cluster coordinators could effectively coordinate access within their cluster without having to take into account interference of devices belonging to foreign clusters. Fluid TH coding could also be applied with the aim of allowing multiple UWB networks to coexist over the same geographical area. The basic idea, in this case, would be to reduce mutual interference among different networks by adopting a different set of fluid TH codes for each network. Devices belonging to different networks should tune features of the adopted fluid TH codes, such as periodicity, in order to concentrate transmission power at different frequencies. Regarding the single network, resource allocation may still be managed through conventional TH multiple access. One may expect that the advantage of network separation by fluid coding would avoid partitioning the available bandwidth between different networks. With the proposed scheme, network organization may also become dynamic: specific nodes in the network could be in charge of scanning the spectrum at network start-up for locating the best locations in the frequency domain where to concentrate transmission power for all devices. At the end of such a preliminary frequency scanning, all the other nodes of the network would be informed of the specific set of parameters that they must adopt for encoding transmission at the physical layer.

VII. Conclusion

This paper investigates the impact of introducing cognitive principles in the design of wireless networks operating under a frequency coexistence regime by analyzing the study case of low data rate IR-UWB systems. Cognition was introduced in a twofold manner. Elected nodes called CNodes become aware of the environment and are capable of controlling their perceived interference by shaping the spectra of radiated signals through pulse selection and position coding. Results obtained by system simulation in different interference scenarios (narrowband vs UWB interferers) indicate that cognition significantly favours radio cohabitation of wireless networks.

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