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Introducing consciousness in UWB networks by hybrid modelling of admission control

Maria-Gabriella Di Benedetto · Guerino Giancola · Maria Domenica Di Benedetto

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Abstract We formalize a model for a self-organizing network of nodes that operate according to the UWB principle based on hybrid modelling formalism. We design the rules that lead to the formation of the network and in particular an admission control procedure that is capable to handle both continuous and discrete perturbations, while maintaining the network in a condition of stability. Cognition is introduced in the model by allowing nodes to adjust their rules of operation based on the perception of the environment by an elected node, serving as the observer, that is aware of context, evaluates, and selects one strategy of operation.

Keywords UWB ad-hoc networks · Cognitive Radio · Hybrid systems · Admission control

1. Introduction

A current concern for designers of wireless communication systems deals with the problem of driving the design based on the concept of a radio capable of adapting to the environment and of adjusting its principles of operation as a function of both external and internal unpredictable events.

Within this framework, an ambitious goal is the design and development of smart wireless devices able to sense the environment, whether this refers to channel or interference patterns, and modify accordingly spectral shape and other features of radiated signals while maintaining compatibility with regulations on emitted radiations. This principle fully fits with the emerging innovative concept of "cognitive radio" aimed at defining and developing technologies that can enable a radio device to adapt its spectrum according to the operating environment, that is, to be aware of the scenario in which it operates [1, 2]. The final goal remains to form wireless networks that cooperatively coexist with other wireless networks and devices. In order for the cognitive radio principle to be applied, radio nodes should consist in software-defined radio platforms that would allow in particular multi band communications. Given their ultra wide bandwidth, Ultra Wide Band (UWB) radio signals must in principle coexist with other radio signals. The problem of possible interference from and onto other communication systems that must be contained within regulated values is thus intrinsic to the UWB radio principle.

In their seminal paper on cognitive radio, Mitola and Maguire [2] introduced the concept of a cognitive cycle where the radio behaves according to five main actions: observe, plan, decide, learn, and act. The capability to perform the cognitive cycle actions would enable the radio to be aware of the environment, evaluate among several strategies, select one strategy of operation, enrich experience by forming new strategies, and perform communication accordingly.

The cognitive radio concept focuses on improving the utilization of the wireless resource, that is, the electromagnetic spectrum. As such, it mainly applies to the behaviour

M.-G. Di Benedetto (✉) · G. Giancola
School of Engineering, University of Rome La Sapienza, Infocom Department,
Via Eudossiana, 18-00184 Rome Italy
e-mail: dibenedetto@newyork.ing.uniroma1.it

G. Giancola
e-mail: giancola@newyork.ing.uniroma1.it

M. D. Di Benedetto
Department of Electrical Engineering and Computer Science,
Center of Excellence for Research DEWS,
Poggio di Roio—67040 L'Aquila, Italy

M. D. Di Benedetto
e-mail: dibenede@ing.univaq.it

of a single node regarding both its transmitter and receiver components, and as a direct consequence to the logic ruling communication over a single link. The implementation of actions such as "observe" may imply communication between nodes and exchange of information on current status of the channel. A remote receiver, for example, may transmit information to an active transmitter regarding the interference context in which it is embedded, in order for the transmitter to adapt transmission features accordingly.

The introduction of the cognitive principle in the logic of the wireless network as regards for example resource management and routing has received until now far less attention. This operation requires extending the cognitive concept to rules of operation that take into account the presence of several nodes in the network as well as their instantaneous configuration. Cognitive principles must be integrated in the rules of interaction between nodes in the network, that is, the set of wireless nodes forms a social network that must be modelled and analyzed as one entity in order to optimize the design.

When cognitive principles affect rules of interaction, cognitive scientists refer to a phenomenon called consciousness. While consciousness appears as a unique feature of the human brain, it is interesting to map the concept onto our context. Consciousness, as reported by cognitive scientists, appears in some brain phenomena while in some other not, where conscious mechanisms are those that are present to awareness [3]. Consciousness is expressed by cognitive mechanisms that are very closely related to our capability in communicating through language. Consciousness is related to tools allowing entities to communicate. As a matter of fact in their work Mitola and Maguire raise the problem of defining a standard language called Radio Knowledge Representation Language (RKRL) through which a cognitive radio can track parameters that refer to elements that are present in a given reference model.

Consider now a set of wireless nodes forming a self-organizing ad-hoc network. Suppose some nodes are cognitive, that is, they are gifted with some sort of intelligence based on adaptive algorithms that take into account the environment and the network in which they operate. Introducing consciousness in the network is thus modelling nodes that operate in a cognitive way and that apply conscious mechanisms to communicate in the network and adapt their behaviour to current network topology and status.

One important concept that needs particular attention is the time scale over which operations such as adaptation take place. A common understanding assumes that all operations occur at clock intervals, or multiples. When constant changes are desired, such as in cognitive radio [1] the clock interval duration is reduced and the system is forced to operate at higher sampling rates with the aim of pushing its behaviour to being continuous.

The above model is limited in its nature. Consider the example of a node in an ad-hoc network. The input-output dynamics might be well described by classical discrete systems formalism, while the phenomenon that should force the node to change its rules of operation might be asynchronous with respect of node dynamics. To complicate matters further, uncertainty may affect system behaviour in substantial ways. Noise as well as unpredictable events such as atmospheric changes or mobility random patterns, to cite a few, are examples of uncertainty that must be incorporated in the model. An accurate modelling of a node in a wireless network requires a mathematical model where continuous and discrete dynamics are appropriately defined.

Hybrid systems are powerful abstractions for modelling complex systems and have been the subject of intense research in the past few years by both the control and the computer-science communities (see e.g. [4]). Particular emphasis has been placed on a unified representation of hybrid models rooted in rigorous mathematical foundations. Moreover, hybrid models have been used in a number of applications to understand the behaviour of systems where digital controls are applied to continuous and discrete processes. The interaction between heterogeneous semantics has been difficult to understand without the rigorous framework offered by hybrid system formalization. A particular area of interest in this domain is represented by networks of control systems acting in a coordinated fashion where communication can be implemented in a variety of ways, wireless and wired, including optical fibers. The effects of non ideal communication channels are well captured by hybrid systems [5–7]. In addition, when the resource is not only scarce but must also be shared, and moreover is time-varying as in wireless channels, an interesting hybrid control problem appears: how to manage the resource so that the overall requirements on the communication network are satisfied.

In this paper we formalize a model for a self-organizing network of nodes that operate according to the UWB principle based on hybrid modelling formalism. We design the rules that lead to the formation of the network and in particular an admission control procedure that is capable to handle both continuous and discrete perturbations while maintaining the network in a condition of stability. Cognition is introduced in the model by allowing the nodes to adjust their rules of operation based on the perception of the environment by an elected node, serving as the observer, that is aware of context, evaluates, and selects one strategy of operation.

The paper is organized as follows. In Section 2, we define the problem and set the basis and main assumptions for the specific system under consideration, and in particular the principles of operation of UWB radio devices. Section 3 focuses on a brief overview of the fundamental principles of hybrid system modelling. Section 4 contains the core of the analysis, that is, the application of hybrid system modelling to the system under consideration that incorporates the cognitive radio concept. In particular, we will show how the proposed model represents the behaviour of each node and of the population of nodes that form the network. Section 5 will set guidelines for future directions of research on modelling wireless networks by hybrid systems.

2. Problem statement and system description

We consider the formation of a self-organizing network of nodes that adopt UWB radio at the physical layer. The UWB signal format is the one typical of Impulse Radio (IR) signals, with Time-Hopping (TH) coding and binary Pulse Position Modulation (PPM) [8], and can be described by the following expression:

$$s(t) = \sqrt{P_{\mathrm{TX}} T_S} \sum_j p_w(t - jT_S - c_j - a_j \varepsilon) \quad (1)$$

where P_{TX} is the average transmitted power, T_S is the pulse repetition period, $p_w(t)$ is the energy-normalized pulse shape, $c_j < T_S$ is the TH code value for pulse j, a_j is the data symbol carried by pulse j, and ε is the PPM shift. Note that the bit interval T_{b} is: $T_{\mathrm{b}} = N_S T_S$, where N_S is the number of transmitted pulses per bit. We assume that transmission power P_{TX} is upper-bounded by a specified maximum power level, indicated as P_{MAX}. The value P_{MAX} may derive from technological limitation or may be determined in compliance with regulatory recommendations, such as power emission masks for UWB transmissions that have been defined by the FCC in the U.S. [9].

A general flat Additive White Gaussian Noise (AWGN) channel model is assumed. The impulse response for the channel between a reference transmitter TX and a reference receiver RX is $h(t) = \alpha\, \delta\, (t - \tau)$, where α and τ are the amplitude gain and propagation delay, respectively. The signal at RX input writes:

$$r(t) = \sqrt{P_{\mathrm{RX}} T_S} \sum_j p_w \left(t - jT_S - c_j - a_j \varepsilon - \tau\right) + n(t) \quad (2)$$

where $P_{RX} = \alpha^2 P_{\mathrm{TX}}$ is the average received power, and $n(t)$ is the cumulative noise at the receiver input.

The optimum single-user receiver for the above system model is composed by a coherent correlator followed by a Maximum Likelihood detector [8]. In each bit period T_b, the correlator converts the received signal into a decision variable Z, which forms the input of the detector. Soft decision detection is performed, that is, the signal formed by N_S pulses is considered as a single multi-pulse signal. The received signal is thus cross-correlated with a correlation mask $m_w(t)$ that is matched with the train of pulses representing one bit. The correlator mask for a generic transmitted bit b_0 writes:

$$m_w(t) = \sum_{j=0}^{N_S - 1} \left(p_w(t - jT_S - c_j) - p_w(t - jT_S - c_j - \varepsilon)\right) \quad (3)$$

The decision variable Z that is present at the correlator output is given by:

$$Z = \int_{\tau}^{\tau + T_b} r(t)\, m_w(t - \tau)\, dt \quad (4)$$

The transmitted bit b_0 is estimated by comparing Z of equation (4) against a zero-valued threshold according to the following rule: when $Z > 0$, decision is "0", while when $Z < 0$, decision is "1", or vice-versa. Let us suppose that $Z < 0$ corresponds to a "0" bit, then for independent and equiprobable transmitted bits, the average BER at the output of the detector is:

$$\mathrm{BER} = Prob\,\{Z < 0 | b_0 = 0\} \quad (5)$$

According to equation (4), a prerequisite for correct detection of transmitted bits is to align the correlator mask with the delayed replica of the transmitted signal $s(t)$, that is, the value of the delay τ must be known at the receiver. This task is generally achieved by grouping information bits into packets, and by providing each packet with a proper synchronization trailer that allows the receiver to estimate the τ value [10]. The synchronization trailer may be composed by a predefined sequence of pulses that is known at the receiver. In this case, the receiver is capable to align the correlator mask with the received signal thanks to the presence of a correlation filter that is matched to the synchronization trailer. For fixed length of the synchronization trailer, performance of the synchronization procedure depends on the signal to noise ratio that is measured on the single pulse. We will denote this quantity as SNR_p, and will assume that the link between TX and RX can be established provided that SNR_p is at least equal to a threshold value SNR_0, which is a system parameter that measures the sensitivity of the receiver with respect to synchronization [11].

As well known, and predictable from equation (1), different pulse shapes can be selected for transmitting data over the wireless channel [12]. In particular, we assume that W different pulses $p_w(t)$, with $w = 1, \ldots, W$, are available for transmission. These waveforms lead to different spectral shapes for the transmitted signals, so that the UWB signal can be adapted to different interference scenarios.

As regards network topology, we suppose that all nodes communicate through one elected node called Conscious Node of the network (CNode). The CNode implements the cognitive paradigm and plays a role of coordination in the network. This should not be confused with a centralized management and control of the resource that in fact, as will be shown later, is to a large extent distributed over the active nodes.

With respect to Multiple Access (MA), TH is used for discriminating among users, according to a method that is commonly indicated as TH Impulse Radio (TH-IR) [10], and which is basically equivalent to a TH-CDMA. Data exchange between the CNode and any other node requires the set-up of a specific channel of communication called Data Channel that is identified by a unique TH code. In such system, a major source of performance limitation can be attributed to Multi User Interference (MUI).

In the presence of MUI at the receiver input, the received signal in equation (2) rewrites as follows:

$$r(t) = \sqrt{P_{\mathrm{RX}} T_S} \sum_j p_w(t - jT_S - c_j - a_j \varepsilon - \tau) + n_e(t) + n_{\mathrm{mui}}(t) \quad (6)$$

where $n_e(t)$ accounts for thermal noise and external interference provoked by wireless devices that operate outside the network, and $n_{\mathrm{mui}}(t)$ accounts for MUI. Introducing equation (6) into equation (4) leads to a decision variable at the output of the correlator given by $Z = Z_u + Z_e + Z_{\mathrm{mui}}$, where Z_u, Z_e, and Z_{mui} are the useful contribution, the external noise contribution, and the MUI contribution, respectively.

For the above receiver architecture, system performance for a given link between one of the N active nodes and the CNode can be expressed in terms of the signal to noise ratio SNR that is measured at the correlator output, which is defined as follows:

$$\mathrm{SNR} = \frac{E_u}{\eta_e + \eta_{\mathrm{mui}}} \quad (7)$$

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 remaining N–1 links. For the system model under examination, under the assumption that all signals are received with same power, one has [8]:

$$E_u = (N_S)^2 \, P_{\mathrm{RX}} T_S \quad (8)$$

where N_s is the number of pulses per bit over the reference link. In addition one has:

$$\eta_e = N_S \, \eta_p(w) \quad (9)$$

$$\eta_{\mathrm{mui}} = N_S \frac{\sigma_m^2(w)}{T_S} \sum_{n=2}^{N} P_{RX} T_S \quad (10)$$

where $\eta_p(w)$ is the variance of noise collected for one single pulse, and $\sigma_m{}^2(w)$ is a MUI weight defined as follows:

$$\sigma_m^2(w) = \int_{-\infty}^{+\infty} \left[\int_{-\infty}^{+\infty} p_w(t+z) \left[p_w(t) - p_w(t-\varepsilon) \right] dt \right]^2 dz \quad (11)$$

According to equations (9) and (10), both noise and the interference terms depend on the waveform that is adopted for transmission. By substituting equations (8), (9), and (10) into equation (7), we obtain that the signal to noise ratio for the reference link is given by:

$$\mathrm{SNR} = \frac{N_s T_s P_{\mathrm{RX}}}{\eta_p(w) + \sigma_m^2(w)(N-1) P_{\mathrm{RX}}} = \frac{1}{R_b} \frac{P_{\mathrm{RX}}}{\eta_p(w) + \sigma_m^2(w)(N-1) P_{\mathrm{RX}}} \quad (12)$$

where $R_b = 1/T_b$ is the bit rate for the link under examination. In evaluating equation (12) we will suppose that all nodes transmit using same T_S. Note that the SNR for a reference RX does only depend on the rate of the reference TX and does not depend, however, on the rate of the interfering users, contrarily to what happens in conventional CDMA systems. In UWB, spreading, in fact, is achieved by transmitting short pulses rather than by increasing rate.

Depending on the characteristics of both $n_e(t)$ and $n_{\mathrm{mui}}(t)$, different analytical relations can be found between the SNR value in Eq. (12) and the BER of Eq. (5). Under the assumption that both $n_e(t)$ and $n_{\mathrm{mui}}(t)$ can be modelled as white Gaussian random processes one has [8]:

$$\mathrm{BER} = \frac{1}{2} erfc\left(\sqrt{\frac{\mathrm{SNR}}{2}}\right) \quad (13)$$

where $erfc(x)$ is the complementary error function of x. Equation (13) has been shown to be valid for systems adopting power control at the reference receiver [13], and networks where devices transmit at high binary rates [14]. For power-unbalanced networks or low data rate networks, accurate BER estimations can be obtained by adopting non-Gaussian approaches for modelling the cumulative noise at the receiver input, such as the Pulse Collision model for IR-UWB communications proposed in [15]. In the present work, we assume validity of the Gaussian approximation when estimating Eq. (13).

Note that by equation (12) one can derive SNR_p, that is:

$$\mathrm{SNR}_p = \frac{T_S P_{\mathrm{RX}}}{\eta_p(w) + \sigma_m^2(w)(N-1) P_{\mathrm{RX}}} \tag{14}$$

The CNode can thus support N active connections with N nodes in the network provided that:

$$\mathrm{SNR}_p \geq \mathrm{SNR}_0 \tag{15}$$

As regards signalling data, we suppose the presence of a common channel called Broadcast Channel.

With respect to traffic modelling, we assume that two types of traffic sources may access the system for transmitting data, called QoS-aware sources (Q sources) and Best Effort sources (B sources).

A Q source is fully characterized in terms of generated traffic and required QoS. As regards traffic, we adopt the standard Dual Leaky Bucket (DLB) network parameters for modelling and shaping data generation [16]. In the DLB approach, each traffic source is characterized by a peak rate p (bits/s), an average rate r (bits/s), a token buffer dimension b (bits), and a maximum packet size M (bits). Note that rates p and r are network parameters that do not take into account the overhead introduced at MAC and physical layers, and can thus result in much lower values than the binary rate R_b used over the air interface and that appears in equation (12). Regarding QoS, each Q source is associated with a maximum tolerable end-to-end delay D (secs), and a minimum percentage of packets F that must reach destination within D. Note that a same set of parameters is used for both real-time and non real-time applications, with no explicit need for defining classes of traffic. Both DLB parameters and QoS specifications cannot be negotiated.

A B source does not require any a-priori specification neither in terms of transmission rate nor in terms of QoS. When a B source enters the system, it is assigned with a fixed amount of transmission power, and will use what is available in terms of resource at best. Therefore, admission control for B sources is only required in order to avoid that the entrance of a new B source might endanger the transmission of Q sources that have already been admitted.

For both Q and B sources, we assume that each generated packet is segmented into MAC protocol data units (MACPDUs) before being transmitted over the radio channel. We suppose that all MACPDUs are composed of a header of L_H bits and a payload of L_P bits, and therefore MACPDUs have all the same size called $L_{\mathrm{MAC}} = L_H + L_P$. The header contains Management information (e.g. MAC ID, addresses, flags...), and the synchronization trailer for receiver synchronization. The payload conveys bits originating from the segmentation of source packets.

3. Basic principles of hybrid system modelling

Hybrid systems are dynamical systems where continuous and discrete dynamics are embedded together to propositional logic. Continuous and discrete variables interact and determine the hybrid system evolution. The hybrid state of a hybrid system is made of two components: the discrete state q_i belonging to a finite set Q and the continuous state x belonging to a linear space $\mathbf{R}^n$. The evolution of the discrete state q_i is governed by an automaton, while the evolution of the continuous state x is given by a dynamical system controlled by a continuous input and subject to continuous disturbances. Whenever a discrete transition occurs, the continuous state is instantly reset to a new value. Even if the intuitive notion of hybrid system is simple, the combination of discrete and continuous dynamics and the mechanisms that govern discrete transitions create serious difficulties in defining its operation precisely. Other complexity stems from the continuous state reset that occurs when the system undergoes a discrete transition. This is why we need formal definitions of the variables that characterize a hybrid system as well as of their evolution in time, as will be defined below:

- The *state variable* of a hybrid system H is made of two components: the discrete state q and the continuous state x. The discrete state belongs to a finite set $Q = \{q_i, i = J\}, J \in \{1, 2, \ldots, N\}, \mathrm{N} \in \mathbf{N}$ and the continuous state takes value in a subset X of $\mathbf{R}^n$. The set $H = \cup_{q \in Q}\{q\} \times X$ is the hybrid state space of H and its elements $h = (q, x) \in H$ are the *hybrid states*.
- The *control input variable* of H is made of two components: the discrete control input σ and the continuous control input u. The discrete control input belongs to a finite set E_C and the continuous control input to the set $\mathbf{R}^m$, $m \in \mathbf{N}$. We assume that the input functions $\mathbf{u} : \mathbf{R} \rightarrow \mathbf{R}^m$ are piecewise continuous.
- The *disturbance variable* of H is made of two components: the discrete disturbance δ and the continuous disturbance input d. The discrete disturbance takes value in a finite set E_E and the continuous disturbance in the set $\mathbf{R}^r$, $r \in \mathbf{N}$. We assume that the disturbance functions $\mathbf{d} : \mathbf{R} \rightarrow \mathbf{R}^r$ are piecewise continuous.
- The *output variable* of H is made of two components: the discrete output p and the continuous output y. The discrete output is assumed to belong to a finite set P and the continuous output to the set $\mathbf{R}^s$, $s \in \mathbf{N}$. The continuous output functions $\mathbf{y} : \mathbf{R} \rightarrow \mathbf{R}^s$ are assumed to be piecewise continuous.

The evolution of the discrete state q of hybrid system H depends on the initial discrete state as well as on the discrete input σ, the discrete disturbance δ and the continuous state x, and is driven by events forcing discrete states to jump. There are three types of discrete transitions:

- *switching transition*, forced by a discrete disturbance $\delta \in E_E$;
- *invariance transition*, determined by the continuous state x reaching some regions of the continuous state space; events inducing invariance transitions are assumed to belong to the finite set E_I and are internally generated by the hybrid system;
- *controllable transition*, determined by a discrete control input $\sigma \in E_C$.

We set $E := E_E \cup E_I \cup E_C$, the set of all events causing discrete transitions of discrete states. A relation $E \subset Q \times E \times Q$ represents the collection of all discrete transitions e $= (q, e, q')$ ∈ E taking the discrete state from q to q' if the event $e \in E$ occurs.

The evolution of the continuous state x depends on the initial continuous state and on the evolution in time of the continuous input u, the continuous disturbance d and the discrete state q. The continuous state and output evolution between two consecutive discrete transitions is modelled by a dynamical system $S(q_i)$ that is assumed to be linear for simplicity and governed by the following equations:

$$\frac{d}{dt}x(t) = Ax(t) + Bu(t) + Dd(t), \quad y(t) = Cx(t) \tag{16}$$

During its evolution in time, the hybrid state $h = (q, x)$ has to satisfy the so-called invariance condition $x \in Inv(q)$, where $Inv(\cdot)$ is called the *invariance map*. Whenever a discrete transition $e \in (q^-, e, q^+) \in E$ occurs, the hybrid state $h^- = (q^-, x^-)$ has to satisfy the so-called guard condition $x^- \in G(e)$, where $G(\cdot)$ is called *guard map* and the continuous state instantly jumps from $x^- \in X$ to a new value $x^+ \in R$ (e, x^-), where $R(. , .)$ is called the *reset map*.

4. Admission control function by hybrid modelling

As indicated in Section 2, network architecture is centralized in the CNode and therefore our analysis is focused on the admission control for uplink connections. In the downlink, in fact, proper orthogonality of signals makes the problem irrelevant. All devices communicate by exchanging data with the CNode, which routes data to other nodes that are located inside its coverage area. Any device has the capability of becoming the CNode of the network. We will start in this paper by analyzing a static scenario where the CNode is elected once, at the beginning of network operation, and is never relocated until the CNode disconnects from the network. We suppose that the role of the CNode is played by the first node coming to life that wants to start organizing a network. This first node starts by activating a beacon message on the Broadcast Channel.

In the following, we will first identify and establish the rules by which N active nodes do actually communicate with the CNode. These rules fix the criteria for determining power and binary rate to be used by a node for transmitting information towards the CNode. Secondly, we will design the procedure of admission control of a candidate node in the network.

4.1. Rules by which N nodes communicate with the CNode

In this section we will illustrate the principles of operation of a network of N nodes. We will first describe the procedure by which nodes compute their transmission power (Section 4.1.1). We will then illustrate how nodes compute their rate, first in the case of Q nodes (Section 4.1.2), and then in the case of B nodes (Section 4.1.3).

4.1.1. Computation of transmission power levels for all nodes

As anticipated in Section 2, different pulse shapes $p_w(t)$, with $w = 1,\ldots,W$ can be selected for transmitting data over the wireless channel. The different waveforms lead to different spectral shapes for the transmitted signals, so that the radiated signal can be adapted to varying interference scenarios. In the case under examination, the selection of the pulse shape is performed by the CNode, based on the following procedure.

We assume that the CNode has the capability of continuously sensing its surrounding environment and of determining the noise floor perceived by its receiver. Different methods and techniques have been proposed in the past for performing this task, including the adoption of multitaper spectral estimation procedures [17], and the use of a large number of sensors to properly sniff the RF environment [1]. Based on environment sensing, the CNode estimates the W different values of the cumulative noise contribution $\eta_p(w)$ in Eq. (9) that would be present at the output of the correlator in correspondence to the W available pulse shapes.

As indicated in Section 2, the selection of a pulse shape affects not only the value of $\eta_p(w)$, but also MUI power at receiver output. To each of the W available pulse shapes, the CNode associates a different MUI weight $\sigma_m^2(w)$ given by Eq. (11).

Based on the knowledge of both $\eta_p(w)$ and $\sigma_m^2(w)$, the CNode can estimate, based on Eq. (14), the value of the power $P_{\min}(w)$ that it must receive from each of the N active nodes in order to comply with the requirement of a threshold SNR_0. This power, identical for each device, can be evaluated from Eq. (14) and be expressed as follows:

$$P_{\min}(w) = \Phi_N(\eta_p(w), \sigma_m^2(w)) \tag{17}$$

where we call $\Phi_N(x, y)$ the Received Power Function (RPF) for N active nodes, expressed by:

$$\Phi_N(x, y) = \frac{x}{T_S}\left(\frac{1}{\mathrm{SNR}_0} - \frac{y}{T_S}(N-1)\right)^{-1} \tag{18}$$

Equation (18) can be used to evaluate the minimum power that must be received by the CNode from each active node in order to guarantee for each connection the condition of Eq. (15). The subscript N for the RPF highlights the number of active nodes, under the above conditions.

Based on Eq. (17), the pulse shape that better adapts with the environment, including both thermal noise and MUI, is the one leading to the smallest $P_{\min}(w)$ value, for $w = 1,\ldots,W$. The CNode can thus determine two factors: the pulse shape to be currently used by nodes $p_w{}^*(t)$ and the corresponding $P_{\min}(w^*)$. These two factors can be obtained as follows:

$$\begin{aligned} w^* &= \arg\min_{w\in[1,W]} P_{\min}(w) \\ P_{\min}(w^*) &= \min_{w\in[1,W]} P_{\min}(w) \end{aligned} \tag{19}$$

Power P_j that node j must use for transmission depends on the power attenuation A_j characterizing the link between node j and the CNode, and can be expressed as follows:

$$P_j = P_{\min}(w^*)A_j \quad j = 1,\ldots,N \tag{20}$$

Note that by assuming that node j is actually communicating with the CNode, we made the implicit hypothesis that $P_j < P_{\mathrm{MAX}}$ for $j = 1,\ldots, N$.

Based on Eq. (20), each device can determine the value of transmission power once informed about the value of $P_{\min}(w^*)$ and once having estimated A_j following a procedure that will be described in Section 4.2.

4.1.2. *Computation of transmission rate for a Q source*

As stated in Section 2, each Q source is associated with the DLB parameters characterizing traffic activity, and two additional parameters specifying QoS in terms of packet transmission delay and packet integrity. Based on the knowledge of both DLB and QoS parameters, the computation of rate R_b that the Q source requires proceeds as follows. Let us consider a generic Q source j, characterized by DLB parameters p_j, r_j, b_j, M_j, and by QoS descriptors D_j, F_j.

The first step is to evaluate the value of transmission delay $D_{0,j}$ experienced by source packets if source j was admitted with that minimum rate $R_{\min,j}$ capable of avoiding overflow of the source buffer. Given the definition of the DLB parameters one has $R_{\min,j} = r_j$, and $D_{0,j}$ is [16]:

$$D_{0,j} = \begin{cases} b_j/r_j & \text{if } p_j > r_j \\ M_j/r_j & \text{if } p_j = r_j \end{cases} \tag{21}$$

The $D_{0,j}$ value in equation (21) must be compared with the maximum packet delay D_j that is required by the source. If $D_j \geq D_{0,j}$, rate $R_{\min,j}$ is sufficient for guaranteeing the QoS delay requirements. Typically, this condition is verified in the presence of non-real-time applications that can tolerate high delays for data transmission. If $D_j < D_{O,j}$, rate $R_{\min,j}$ is not sufficient for ensuring the requested QoS. Typically, this is the case of real-time applications that have severe requirements in terms of transmission delay. The computation of the transmission rate for both cases can be generalized by introducing the requested delay $D_{R,j}$, that is defined as follows:

$$D_{R,j} = \min\{D_j, D_{0,j}\} \tag{22}$$

Given $D_{R,j}$, the transmission rate needed by the source under examination is [16]:

$$R_j = \begin{cases} \dfrac{p_j\cdot b_j - r_j\cdot M_j}{D_{R,j}\cdot(p_j-r_j)+b_j-M_j} & \text{if } p_j > r_j \\ \dfrac{M_j}{D_{R,j}} & \text{if } p_j = r_j \end{cases} \tag{23}$$

Note that the rate in Eq. (23) does not take into account the effect of the overhead that is required for each MACPDU. Given R_j, the effective rate $R_{b,j}$ that must be considered for transmission at the physical layer is in fact:

$$R_{b,j} = \frac{L_{\mathrm{MAC}}}{L_P}R_j \tag{24}$$

Based on Eqs. (20) and (24), each Q source can determine both power P_j and rate $R_{b,j}$ that must be used for transmitting data towards the CNode. Given P_j and $R_{b,j}$, it is also possible to evaluate from Eq. (13) the average BER_j that is experienced at the CNode:

$$\mathrm{BER}_j = \Theta_N(R_{bj}, P_{\min}(w^*), \eta_P(w^*), \sigma_m^2(w^*)) \tag{25}$$

where we call $\Theta_N(x, y, z, v)$ the Receiver Error Function (REF), which writes:

$$\Theta_N(x, y, z, v) = \frac{1}{2}erfc\left(\sqrt{\frac{1}{2x}\frac{y}{z+v(N-1)y}}\right) \tag{26}$$

In the absence of error correction in the MAC, all bits in the MACPDU must be correct for the MACPDU to be correct, and therefore the source experiences an average MACPDU error rate MER_j expressed by:

$$\mathrm{MER}_j = 1 - (1 - \mathrm{BER}_j)^{L_P} \tag{27}$$

In terms of error rate on the network packet PER_j one has:

$$\mathrm{PER}_j = 1 - (1 - \mathrm{MER}_j)^{\lceil M_j/L_P \rceil} \tag{28}$$

Given PER_j of Eq. (28), the percentage Ψ_j of network packets that are correctly delivered at the CNode is: $\Psi_j = 100(1-\mathrm{PER}_j)$. Note that by assuming that node j is actually communicating with the CNode, we made the implicit hypothesis that $F_j < \Psi_\mathrm{j}$.

4.1.3. *Computation of transmission rate for a B source*

As indicated in Section 2, B sources have no specific QoS requirements and evaluate the best available transmission rate.

In this paper, we propose a strategy that can be adopted by a *B* node. We assume that the transmission rate for a generic B source j corresponds to the binary rate $R_{b,\,j}$ which maximizes a node-specific and rate-dependent utility function $U_j(R)$. This utility function serves as a metric for satisfaction of source j when transmitting at R bits/s on the physical layer.

Previous work typically related to power control for CDMA networks define the utility function as the effective number of bits transmitted per battery life that is achieved by source when transmitting at given power and rate [18]. Based on the above, we propose a utility function that can be expressed as follows:

$$U_j(R) = \frac{E_j}{P_j}\frac{L_P}{L_{\mathrm{MAC}}} R \cdot \beta(R) \tag{29}$$

where E_j is the energy content of the battery of source j,P_j is the transmission power for node j determined according to Eq. (20), and $\beta(R)$ is an *efficiency function*. The efficiency function quantifies the loss in performance that is experienced over the link as the node attempts to increase its rate. The efficiency function must thus vary from 0 to 1 as the transmission rate decreases from infinity to zero. Based on [18], we select for the efficiency function the average packet success rate (1 – PER_j) derived from Eq. (28). We obtain:

$$U_j(R) = \frac{E_j R}{P_j}\frac{L_P}{L_{MAC}}\left(1 - \mathrm{MER}_j\right)^{\lceil M_j/L_P \rceil} \tag{30}$$

Equation (30) indicates that as source j attempts to increase R for fixed P_j, a higher number of packet errors occur at the network level because of an increase in MER_j. As a matter of fact, for B sources MER_j depends upon R. Based on equation (27) and incorporating properties of $\beta(R)$ we define the following relation as valid for B sources:

$$\mathrm{MER}_j(R) = 1 - (1 - 2\mathrm{BER}_j(R))^{L_P} \tag{31}$$

The presence of a factor 2 multiplying the $BER_j(R)$ term in Eq. (31) (vs. a factor 1 in Eq. (27)) is such that the efficiency function $\beta(R)$ goes to zero for high data rates. Without the '2' factor, in fact, one node could experience efficiency of transmission greater than zero even for exceptional high transmission rates. When R tends to infinity, SNR at correlator output tends to zero (see Eq. (13)). Even for near-zero SNR values, however, BER never oversteps 0.5: no matter what level of noise is present at RX, the detector can always randomly guess the value of a transmitted bit with a 0.5 probability of success. As a consequence, the probability that the receiver correctly guesses a MACPDU never goes to zero, and, therefore the probability of correct network packet detection never goes to zero. By adding a '2' factor, we translate BER into a measure of uncertainty where '1' corresponds to chance, and let the utility function in Eq. (29) tend to zero as transmission rate R goes to infinity.

The average BER_j in Eq. (31) can be evaluated similarly to the case of Q sources, that is, based on Eq. (25):

$$U_j(R) = \frac{E_j R}{P_j}\frac{L_P}{L_{MAC}} \left(\left(1-2\Theta_N\left(R, P_{\min}\left(w^*\right), \eta_p\left(w^*\right), \sigma_m^2\left(w^*\right)\right)\right)^{\lceil M_j/L_P \rceil}\right) \tag{32}$$

In order to better illustrate the utility function we computed a case example of a utility function that is represented in Fig. 1. The plot in Fig. 1 was obtained for a reference scenario with $N = 50$, $T_S = 50$ ns, $\eta_p(w^*) = -196.0871$ dBW/Hz, $\sigma_m^2(w^*) = 1 \cdot 10^{-12}$ s, $\mathrm{SNR}_0 = 9$ dB, $E_j = 2.15 \cdot 10^{-9}$ Joule, $M_j = 1024$ bits, $L_P = 512$ bits, $L_{MAC} = 578$ bits.

The shape of the utility function of Figure 1 can be interpreted as follows: for low data rates the number of bits that are sent to destination is quite low because TX is generating a high number of pulses per bit N_S and as such is rapidly consuming its battery. Up to a certain threshold, an increase in rate, that is a decrease in N_S, corresponds to an increase in utility since a higher number of bits are being transmitted for same battery life. Beyond the threshold, user satisfaction rapidly decreases when rate increases due to degradation in the transmission quality.

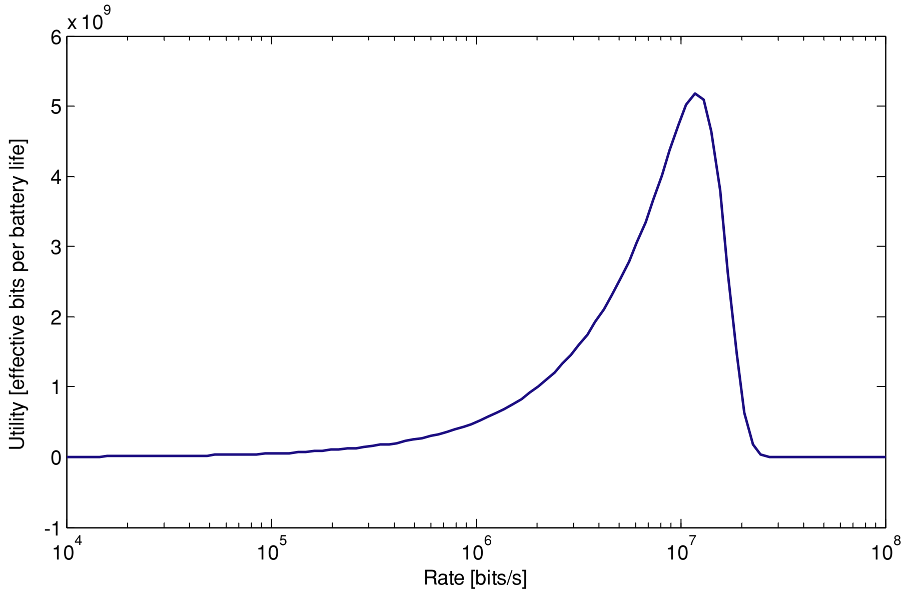


Fig. 1 Utility function expressed in number of effective bits per battery life vs. transmission rate for a case example characterized by the following set of parameters: $N = 50$, $T_S = 50$ ns, $\eta_p(W^*) = -196.0871$ dBW/Hz, $\sigma_m{}^2(W^*) = 1 \times 10^{-12}$ s, $SNR_0 = 9$ dB, $E_j = 2.15 \cdot 10^{-9}$ Joule, $M_j = 1024$ bits, $L_P = 512$ bits, $L_{MAC} = 578$ bits

It can be demonstrated [6, 18] that the value of $R_{b,j}$ that maximizes the utility function is such that:

$$\dot{U}_j(R_{b,j}) = \left.\frac{\partial U_j(R)}{\partial R}\right|_{R=R_{b,j}} = 0 \tag{33}$$

Resource allocation for B sources is thus operated as follows. Transmission power is determined by each node based on the knowledge of both $P_{\min}(w^*)$ required at the CNode, and an estimate of power attenuation A_j characterizing the link (see Eq. (20)). Transmission rates are determined at each node by solving Eq. (33).

If we denote by N_B the number of B sources that are currently connected with the CNode ($N_B \leq N$), it is possible to demonstrate that there exists a unique set of rates $R_{b,j}$ with $j = 0,\ldots,N_B$, which satisfies:

$$\dot{U}_j(R_{b,j}) = 0 \quad \text{with} \quad j = 0, \ldots, N_B \tag{34}$$

The proof of the above theorem can be found in [18], and derives from the quasi-concavity of the utility function in Eq. (32). Note that the set of rates that verifies Eq. (34) corresponds to a Nash equilibrium for the distributed rate allocation procedure that is performed by the B sources [6]. In other words, there is no B source j that can improve its utility with respect to $U(R_{b,j})$ by a unilateral change in its transmission parameters, that is, by changing its rate $R_{b,j}$. In addition, because a change of transmission rate for a given user j does not affect in any way the utility of the other users, the solution indicated by Eq. (34) is also Pareto efficient [18].

4.2. Rules by which a candidate node is admitted in the system

The model for the system under consideration in light of the hybrid system concepts can be summarized as reported in Fig. 2, where the whole network is modeled as a finite-state automaton.

Each discrete state of the automaton corresponds to the presence in the network of N active nodes and one CNode. Note on Fig. 2 that in each state the system receives different inputs ranging from RF stimuli from the environment, in agreement with the model proposed by [2], that are processed by the CNode, to indicators of the attenuation that is present over the N active links. These attenuation indicators are used by the active nodes for evaluating potential transmission parameters as well as their capability to comply with the above.

The automaton can move from state q_N to state q_{N+1} or to q_{N-1}. Let us analyze these two possible transitions separately and let us refer to Figure 3 showing the details of generic state q_N.

The transition from state q_N to upper state q_{N+1} is a *controllable transition* determined by the discrete control input given by the CNode and represented by the admission of a candidate node, either Q or B, in the network.

The transition from state q_N to lower state q_{N-1} is associated with the disconnection of one node from the network. This disconnection can be provoked by one of the two following events:

Event 1. A node leaves the network because its activity is terminated for reasons that range from no more data packets to transmit, to node failure, to power exhaustion.

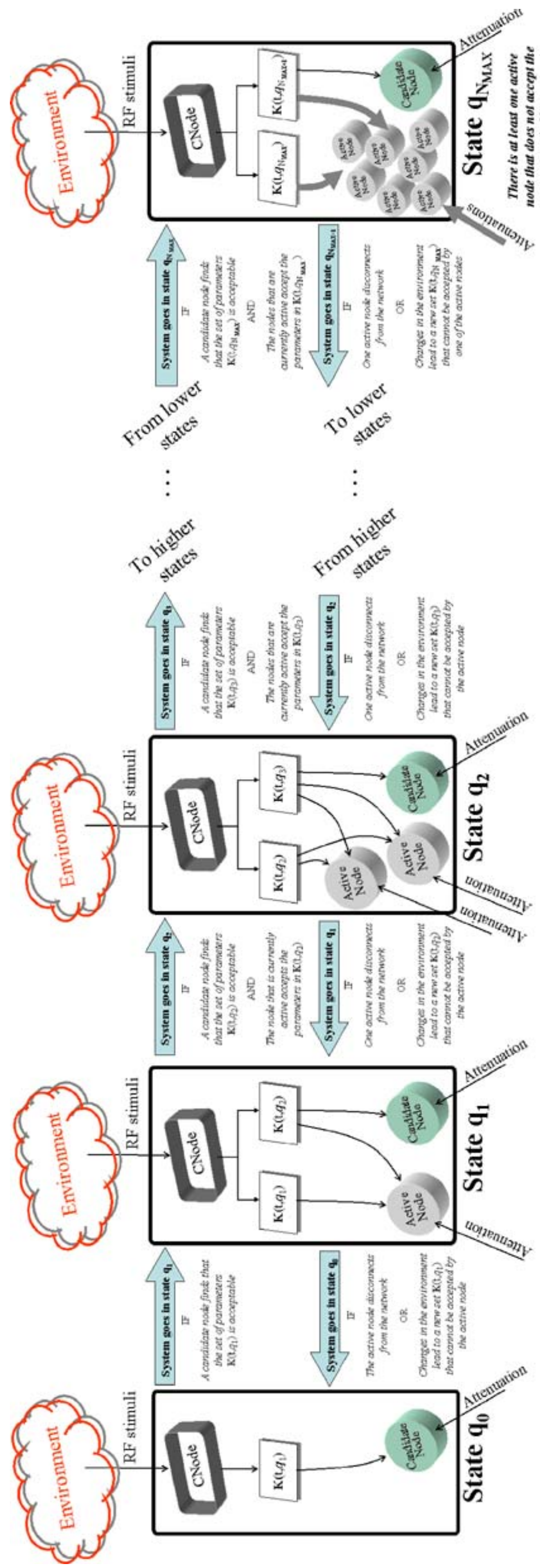
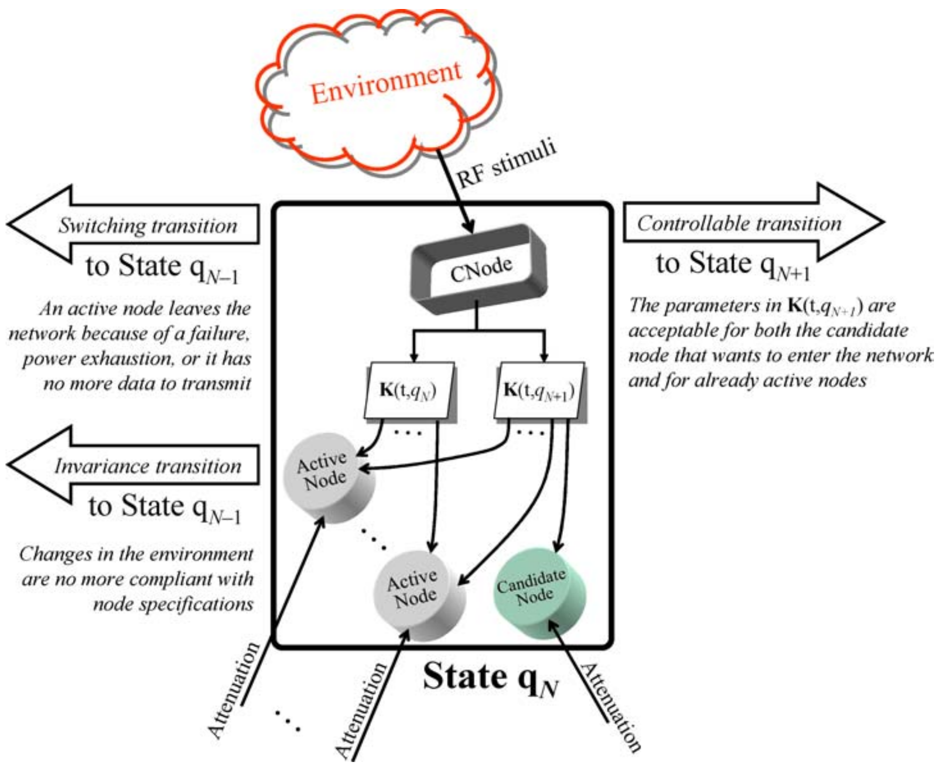


Fig. 2 Hybrid model of a wireless network by a finite-state automaton

Fig. 3 Model for state q_N of the hybrid system.



Event 2. Changes in the environment, as sensed by the CNode, and in radio propagation, as perceived by the active nodes, are no more compliant with node's requirements.

Inroduce the lower state transition provoked by Event 1 is a *switching transition*. The disruption of a node as in Event 1 can be in fact modeled as a discrete disturbance forcing the automaton to switch to a lower state.

In Event 2, the phenomenon is different. What we observe here is that the conditions that allow the system to operate in state q_N are violated. These conditions form the invariance conditions set characterizing state q_N, and Event 2 represents the situation where elements in the network cease to comply with such conditions. This transition is thus an *invariance transition*.

In state q_N, the CNode has activated N links with N active nodes. Note on Figure 3 the interaction of the network with the environment through the CNode. We suppose that changes in the environment are related to events such as the arrival of an interferer or the creation of a coexisting network, and as such the temporal scale of such perturbations is sensibly longer with respect to events that occur in the MAC, such as packet generation. As a good conscious node should do, the CNode sends, during connection, using piggybacking for example, continuous updates regarding transmission parameters. These parameters are in turn used by the active node for adjusting its communication. This time-varying set of parameters named $\mathbf{K}(t, q_N)$, where t is time, is formed as follows:

1. the waveform (w^*) that must be used for pulse shaping;
2. the power level $P_{\min}(w^*)$ that is required at the CNode;
3. the noise level $\eta_p(w^*)$ that is currently measured at the CNode;
4. the MUI weight $\sigma_m{}^2(w^*)$;
5. the number of active nodes N.

Within the above set one can identify in the first two parameters (w^*) and $P_{min}(w^*)$, constraints that are imposed to the nodes in the network. The noise level $\eta_p(w^*)$ can be interpreted as a continuous disturbance. The MUI weight $\sigma_m{}^2(w^*)$ and the number of active nodes N are information characterizing the current system state.

The time-varying set of parameters $\mathbf{K}(t, q_N)$ is evaluated at the CNode using the RPF. We suppose that the signal containing the above information is sent by the CNode at a fixed power level that is pre-determined and known by all nodes.

Each active node j receives the signal conveying $\mathbf{K}(t, q_N)$ and based on received power level can estimate the attenuation A_j characterizing its path to the CNode. Node j determines both power and rate to be used in its future transmissions to the CNode according to the procedure presented in Section 4.1. This computation is based on the twin function of RPF, that is REF, (see Eq. (26)). Let us assume for now that the possible variations of the environment that reflect in the $\mathbf{K}(t, q_N)$ set are tolerable by all nodes in the network.

In parallel to evaluating and communicating $\mathbf{K}(t, q_N)$, the CNode evaluates the eventual transition to state $N+1$ by computing a hypothetical RPF of state q_{N+1} and corresponding $\mathbf{K}(t, q_{N+1})$. This information is broadcasted by the CNode on the Broadcast Channel, and serves to the N active nodes in order to evaluate whether they are willing to move to state $N + 1$. Note that a transition to state $N+1$ may only be impeded by a Q node that might not be in the condition of hitting its QoS for the $N+1$ conditions. B nodes are in fact more flexible and a parameter change may only reflect in a change in their rate. Note that in state q_0 this set $\mathbf{K}(t, q_0)$ corresponds to the beacon that was mentioned previously.

Let us now describe in more detail the controllable transition between state q_N and state q_{N+1}. This controllable transition is governed by the admission control function. Two conditions that correspond to guard conditions must be verified in order for this transition to take place. First, all active nodes must check that constraints for transition are compatible with their specifications and inform the CNode, by piggybacking for example. Willingness to transition of all nodes is a necessary condition for transition. Second, a candidate node that listens to $\mathbf{K}(\mathrm{t}, q_{N+1})$ must agree in accepting those constraints.

Note that the above mechanism automatically limits the number of active nodes in the network to N_{MAX}, which is not pre-defined at network start-up and rather depends on the overall network evolution. In particular, N_{MAX} depends upon node distribution in the population in terms of number and features of Q nodes vs. number of B nodes.

Note that in realistic scenario the CNode itself may disconnect for a variety of reasons. While in the current analysis we suppose the CNode to be relatively stable, the above rules can be extended possible relocation of the CNode. We will investigate in the future scenarios where CNode handovers are ruled by the goal of optimizing the quality of the transmission and the efficiency in the use of the available resource.

5. Future research directions

Hybrid system formalism offers the framework for modeling the behavior of self-organizing networks. Thanks to this formalism we characterized self-organizing network dynamics as a discrete finite-state automaton where, for each state, state-specific rules of operation govern the evolution of the network itself. As presented in the paper, we described the rules of formation of a self-organizing network of nodes operating according to the UWB principle. Given the ultra wide bandwidth of radiated signals, radio devices operating under UWB rules must in fact coexist with severely interfered environments and must control their behavior in order to favor coexistence. In other words, these radios must be capable to adapt to ever changing operating conditions. In the proposed model, this is achieved by introducing conscious mechanisms in the analysis process that is used by nodes for determining whether changes in the global network state are appropriate.

In this framework, we achieved the goal of designing rules that lead to the formation of the network and in particular an admission control procedure capable of handling both continuous and discrete perturbations while maintaining the network in a condition of stability. Cognition was introduced in the model by allowing nodes to adjust their rules of operation on the basis of the perception of the environment by an elected node, serving as the observer and called the Conscious Node, that is aware of context, evaluates, and selects one strategy of operation.

The interest of introducing hybrid system modeling has been twofold. First, functional specifications of the system have been precisely expressed using the hybrid formalism. Some functionalities that in the present model are associated to active nodes could instead be associated to the CNode or vice-versa. Using the hybrid system model, it is possible to understand how functional specifications and distribution of functional specifications among different components of the system may be optimized. On the other hand, our modeling has allowed a formal description of the behavior of this complex problem, which is of help in understanding some important properties of the system. For example, in the simplified model that we proposed for the CNode, all necessary parameters are computed at each instant of time for *each* pulse shape. This is not only a heavy task, but does not take into account which pulse shape the receiver is presently selecting, hence does not take advantage of the actual state of the receiver. An extension of this work will also consider a dynamical behavior for the CNode where the choice of the pulse not only depends on the environment but also on its present state. Another aspect that needs attention, in particular when the CNode dynamically adapts the parameters to external stimuli, is the stability of the overall system, which may be analyzed on the associated hybrid model.

Finally, an important question for the communication network designer is the prediction of the maximum number of nodes N_{MAX} in the network. In the hybrid system literature, the discrete structure of the hybrid system, represented by the discrete states, and in particular by their number, is traditionally fixed. In the application we illustrated, this assumption does not hold and methods must be determined for the estimation of the maximum number of nodes N_{MAX} that would allow an acceptable behavior of the self-organizing network.

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Maria-Gabriella Di Benedetto obtained her Ph.D. in Telecommunications in 1987 from the University of Rome La Sapienza, Italy. In 1991, she joined the Faculty of Engineering of University of Rome La Sapienza, where currently she is a Full Professor of Telecommunications at the Infocom Department. She has held visiting positions at the Massachusetts Institute of Technology, the University of California, Berkeley, and the University of Paris XI, France. In 1994, she received the Mac Kay Professorship award from the University of California, Berkeley.

Her research interests include wireless communication systems and speech science. From 1995 to 2000, she directed four European projects for the design of UMTS. Since 2000, she has been active in fostering the development of Ultra Wide Band (UWB) radio communications in Europe. Within the 5th framework, she directed for the Infocom Dept. two European projects (whyless.com and UCAN) aimed at the design and implementation of UWB ad-hoc networks. Currently, within the 6th EU Framework, her "Networking with UWB" research group participates in the PULSERS Integrated Project which will integrate UWB research and development in Europe for the next years, and in the LIAISON Integrated Project as regards the application of UWB to location-based services. She also participates in the HYCON network of excellence. Dr. Di Benedetto has co-edited several Special Issues on UWB communications and networks for several Journals including IEEE JSAC, Journal of Communications and Networks, Mobile Networks and Applications, Eurasip.

In 2004, Dr. Di Benedetto co-authored with G. Giancola the first published book on UWB for communications titled "Understanding Ultra Wide Band Radio Fundamentals" and published by Prentice Hall. She recently completed the co-edition of two new books on UWB that will be published by 2005: UWB Communication Systems—A comprehensive overview, with T. Kaiser, D. Porcino, A. Molisch, and I. Oppermann, Hindawi Publishing Corporation, 2005, and Ultra Wideband Wireless Communications with H. Arslan and Z.N. Chen, John Wiley & Sons, Inc., 2005.

Guerino Giancola received the "Laurea" degree (magna cum laude) in Telecommunications Engineering, and the Ph.D. degree in Information and Communication Engineering from University of Rome La Sapienza, in 2001 and 2005, respectively. He is currently a research affiliate at the INFOCOM Department at University of Rome La Sapienza, where is actually holding the course of "Electrical Communications" for the degree on Electronic Engineering. His research interests include the analysis and modelling of Multi User Interference in Impulse Radio systems, and the design of Medium Access Control functions and protocols for UWB ad-hoc networks. Guerino Giancola recently co-authored with Prof. Maria-Gabriella Di Benedetto a book on Ultra Wide Band from radio to the network, titled "Understanding Ultra Wide Band Radio Fundamentals" and published by Prentice Hall in June 2004. He is now involved in the European project "PULSERS—Pervasive Ultra wideband Low Spectral Energy Radio Systems" and in the European Network of Excellence "HYCON–Hybrid Control: Taming Heterogeneity and Complexity of Networked Embedded Systems". Guerino Giancola is a member of the IEEE Communication Society.
E-mail: giancola@newyork.ing.uniroma1.it

Maria Domenica Di Benedetto obtained the "Dr. Ing." degree (summa cum laude) of Electrical Engineering and Computer Science, University of Roma "La Sapienza" in 1976 (Mosè Ascoli Best Student Award). In 1981, she obtained the degree "Docteur-Ingénieur" and in 1987 the degree "Doctorat d'Etat ès Sciences", Université de Paris-Sud, Orsay, France. From 1979 to 1983, she had been Research Engineer at the scientific centers of IBM in Paris and Rome. From 1983 to 1987, she had been Assistant Professor at the University of Roma "La Sapienza". From 1987 to 1990, she had been Associate Professor at the Istituto Universitario Navale of Naples. From 1990 to 1993, had been Associate Professor at the University of Roma "La Sapienza". Since 1994, she has been Professor of Control Theory at University of L'Aquila. From 1995 to 2002, she was Adjunct Professor, Department of EECS, University of California at Berkeley. In 1987, she was Visiting Scientist at MIT; in 1988, 1989 and 1992, Visiting Professor at the University of Michigan, Ann Arbor; in 1992, Chercheur Associé, C.N.R.S., Poste Rouge, Ecole Nationale Supérieure de Mécanique, Nantes, France; in 1990, 1992, 1994 and 1995, McKay Professor at the University of California at Berkeley. Her research interests revolve around nonlinear control and hybrid systems. She was Associate Editor of the IEEE Transactions of Automatic Control and has been Subject Editor of the International Journal of Robust and Nonlinear Control since 1995. Since 2005, she has been a member of the IFAC Technical Committee on Discrete Event and Hybrid Systems. Since 2000, she has been the Director of the Center of Excellence for Research DEWS on "Architectures and Design methodologies for Embedded controllers, Wireless interconnect and System-on-chip", University of L'Aquila. She is IEEE Fellow and Chairperson of the Standing Committee on Fellow Nominations, IEEE Control Systems Society.