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Hybrid Modelling of Ultra Wide Band Self-organizing Networks

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Abstract—**Hybrid systems formalism is used to derive a model for a self-organizing network of nodes that operate according to the UWB principle. We model 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. Nodes may 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.**

I. INTRODUCTION

DURING the past few years, hybrid systems have been the subject of intense research in both the control and the computer-science communities [1]. Hybrid systems offer in fact the analytical framework for modeling complex systems where continuous dynamics and discrete processes tightly interact. In this context, an area of particular interest is the application of hybrid models for the design of algorithms and protocols in wireless self-organizing communication networks. In a wireless self-organizing network, nodes are forced to adapt the rules of operation according to changes and perturbations that are in general asynchronous with respect to node dynamics. In addition, nodes must cope with noise and other unpredictable events,

such as atmospheric changes or mobility random patterns, which introduce additional uncertainty in node behaviour. Hence, an accurate modelling of a node in a wireless network requires a mathematical framework where continuous and discrete dynamics are appropriately defined.

In this paper, we formalize a model for a self-organizing network of nodes that operate according to the Ultra Wide Band (UWB) principle [2]. Given the ultra wide bandwidth of radiated signals, radio devices operating under UWB rules must coexist with severely interfered environments and must control their behavior in order to favor coexistence. In other words, UWB radios must be capable to adapt to ever changing operating conditions. In the proposed model, this is achieved by introducing cognitive mechanisms [3], [4] in the analysis process that is used by the nodes for determining whether changes in the global network state are appropriate. Network nodes are thus provided with the ability to adapt their rule of operation based on the analysis of the environment in which they operate. The cognitive principle is also integrated in the rules of interaction between nodes. Based on the above assumption, the set of wireless nodes is considered in our model as a social network that is modelled and analysed as one single entity.

In the above context, our aim is to design the rules that lead to the formation of the network and, in particular, to design an admission control procedure that is capable to handle both continuous and discrete perturbations. The network is maintained in a condition of stability by construction, in the sense that there are no oscillations in the network behavior due to changes in the constraints. Using the hybrid system formalism, we characterize in Section II the network dynamics as a discrete finite-state automaton where, for each state, specific rules of operation govern the evolution of the network itself. 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 (the Conscious Node, or CNode), serving as the observer, that is aware of context, evaluates, and selects one strategy of operation. In Section III, we present some concluding remarks highlighting open problems that may be formally stated and analyzed using the proposed hybrid model.

II. ADMISSION CONTROL BY HYBRID MODELLING

In the proposed model of a self-organized network, each discrete state of the automaton corresponds to the presence in the network of N active nodes communicating with one CNode (Figure 1). Thus, to each state of the system is associated the discrete state variable q_N, which indicates the number of active nodes that are allowed to transmit data over the wireless channel. In each state, the system receives different inputs ranging from Radio Frequencies (RF) stimuli from the environment in agreement with the model proposed by [3], to indicators of the attenuation that is present over the N active links.

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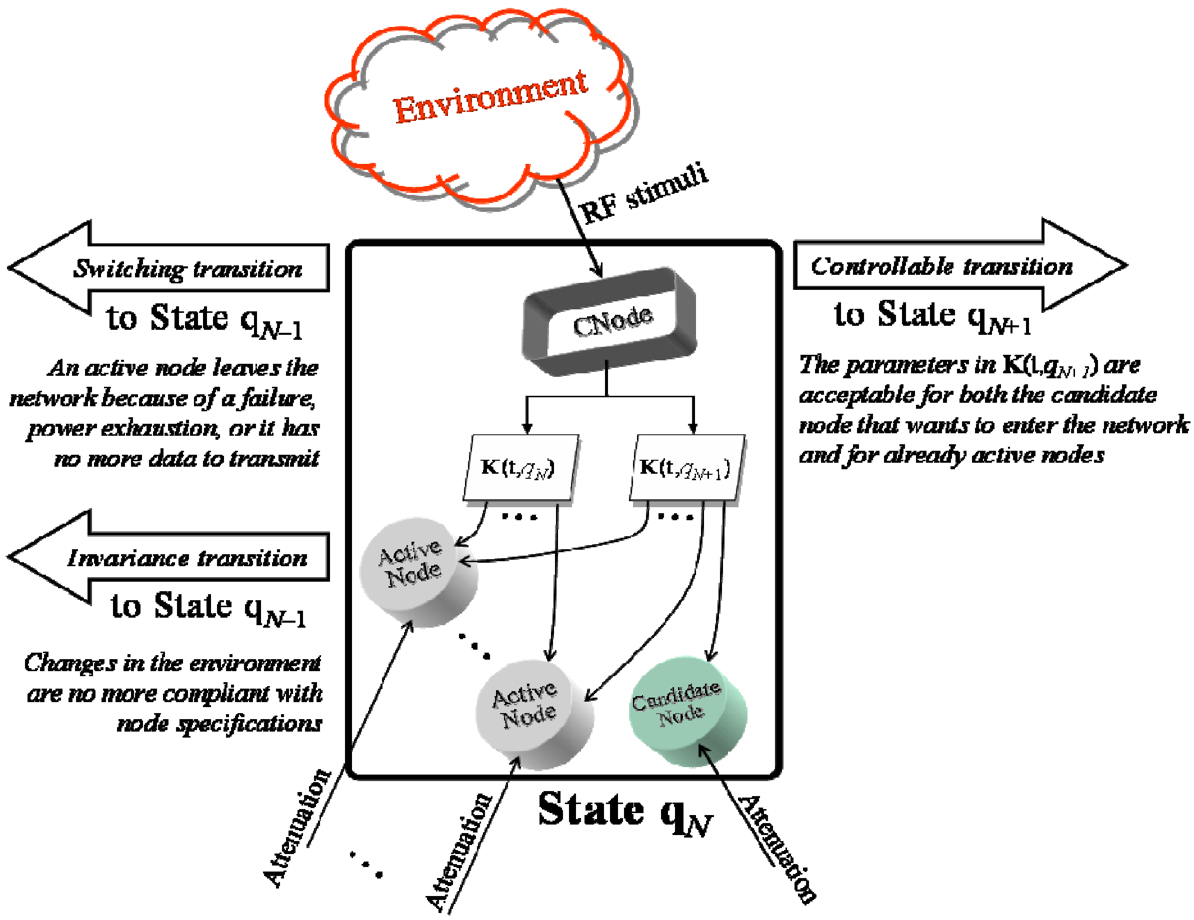

Fig. 1: Model for a generic state q_N of the hybrid system

These attenuation indicators are used by the active nodes for evaluating at time t both potential transmission parameters as well as their capability to comply with the transmission constraints that are communicated by the CNode through a time dependent set of parameters named $\mathbf{K}(t, q_N)$.

In state q_N, the CNode has activated N links with N active nodes. The network interacts with the environment through the CNode (see Figure 1). 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 other events such as packet generation. The CNode sends, during connection, continuous updates regarding transmission parameters. In turn, these parameters are used by the active node for adjusting its communication. This time-varying set of parameters $\mathbf{K}(t, q_N)$, is formed as follows:

1. the waveform w^* that must be used for pulse shaping. Different pulse shapes can be selected for transmitting data over the wireless channel; w^* is the one that better adapts with the environment, as well as with thermal noise and Multi User Interference (MUI) patterns;

2. the power level $P_{min}(w^*)$ that is required at the CNode in order to comply with the requirement of a given signal to noise ratio threshold; 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

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

3. the noise level $\eta_p(w^*)$ that is currently measured at the CNode;

4. the MUI weight $\sigma_m^2(w^*)$ that is associated by the CNode to the pulse shape w^*, corresponding to a measure of the effect of the presence of MUI;

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 acting on the overall system dynamics. The MUI weight $\sigma_m^2(w^*)$ and the number of active nodes N are information characterizing the current system state.

The time dependent set of parameters $\mathbf{K}(t, q_N)$ is evaluated at the CNode using the Received Power Function for N active nodes, according to principles that are peculiar to UWB systems (see [5]). We suppose that the signal containing the above information is sent in broadcast 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, on the basis of 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 a procedure presented in [5]. We assume 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.

As indicated in Fig. 1, the automaton representing the proposed system can move from state q_N to state q_{N+1} or to q_{N-1}.

According to the hybrid formalism, 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 in the network. The procedure is as follows. In parallel to evaluating and communicating $\mathbf{K}(\mathrm{t}, q_N)$, the CNode evaluates the possibility of transitioning to state $N+1$ by computing a hypothetical set of transmission constraints for the state q_{N+1} and the corresponding $\mathbf{K}(t, q_{N+1})$. The use of this information is twofold. First, it serves to the N active nodes in order to check whether constraints for transition are compatible with their specifications and inform the CNode. Willingness to transition of all nodes is a necessary condition for transition. Second, the information in $\mathbf{K}(t, q_{N+1})$ is used by candidate nodes for evaluating their willingness to join the network. A candidate node that listens to $\mathbf{K}(\mathrm{t}, q_{N+1})$ must agree in accepting those constraints for the transition to take place. The two conditions above correspond to guard conditions that must be verified in order for this transition to take place.

The mechanism described above 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.

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:

(i) 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.

(ii) 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.

The lower state transition provoked by the event (i) is a *switching transition*. The disruption of a node as in (i) can be in fact modeled as a discrete disturbance forcing the automaton to switch to a lower state.

In (ii), 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 (ii) represents the situation where elements in the network cease to comply with such conditions. This transition is thus an *invariance transition* that occurs when changes in the environment are no more compliant with system requirements.

III. FUTURE WORK DIRECTIONS

Using the hybrid systems formalism, we characterized self-organizing network dynamics as a finite state automaton where, for each discrete state, specific rules of operation govern the evolution of the network itself.

Several benefits are obtained by introducing the hybrid system model for the design of UWB self-organizing networks:

- The formal description resulting from the adoption of the hybrid system formalism allows a better understanding of some important properties of the system. As an example, it is possible to characterize the trade off that exists between the complexity of a real-time and precise scanning of the external environment vs. the improvement in system efficiency that is achieved when the nodes can rapidly adapt themselves to the varying condition of the operating scenario. Based on this trade-off, we could investigate the existence of sub-optimal but computational efficient strategies, where the capability of the nodes to adapt to the external environment is limited and depends upon the current state of the automaton.

- Using the hybrid system model, it is possible to optimize the distribution of functional specifications among the different components of the system. For example, we can analyze how system performance is affected whenever some of the functionalities that are associated to active nodes are associated to the CNode and vice-versa.

- The hybrid formalism may help to predict in which states the automaton will spend most of the time, or the maximum number of nodes of the network. This information is of fundamental importance for network designers.

- The characterization of the wireless network as a hybrid system facilitates the analysis of the stability [6] of the overall system, which is not an easy task when assuming that the nodes dynamically adapt transmission parameters and rules of operation to the external stimuli.

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