Chapter 1

Cognitive routing models

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This chapter investigates the effect of introducing cognitive mechanisms in the routing function of a wireless network. First, a review of existing proposals for introducing cognition in the routing process is presented. Next, a routing cost function incorporating measurements of the instantaneous behaviour of the external world, represented by the interference suffered by overlaid networks, is defined. The function is applied in the framework of IEEE 802.15.4a-like low data rate and low cost networks for mixed indoor/outdoor communications. The behavior of a network of nodes that implements the cognitive approach in the routing module is analyzed by simulation, measuring network performance and network lifetime. Results indicate that the introduction of a mechanism that allows the routing strategy to adapt to the environment and to adjust its principles of operation as a function of both external and internal unpredictable events leads to a remarkable improvement in network performance.*

1.1. Introduction

The introduction of the cognitive principle in the logic of a wireless network 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. In this perspective, the design goal moves from the definition of a single smart device to a network of smart devices that must be capable of efficiently coexist in a given geographical area by using co-

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operation. This goal requires the integration of cognitive principles in the rules of interaction between nodes in the network: the set of wireless nodes should form a social network that must be modelled and analyzed as one entity in order to optimize the design of network functions such as resource management and routing.

In this investigation we focus on the introduction of the cognitive principle in the logic of a wireless network as regards routing. To this aim, we first review existing investigations on the application of the cognitive principle to the routing problem. Next, we describe our approach to cognitive routing for wireless networks, originally proposed in [1]. We assume that the routing function incorporates measurements of the instantaneous behaviour of external world, as represented for example by current network status in terms of interference suffered by an overlaid network. The framework that we consider for our research refers to low data rate and low cost networks for mixed indoor/outdoor communications investigated within the IEEE 802.15.4a Task Group ([2, 3]). Within this group, an Impulse Radio Ultra Wide Band (IR-UWB) physical layer, capable of providing the accurate ranging information required for accurate positioning was adopted. The IEEE 802.15.4a Task Group concluded its activity in March 2007, when the new standard was released [3].

The chapter is organized as follows. In Section 1.2 we review previous work on the cognitive routing problem, and provide a description of the main contributions on this topic. In Section 1.3 we introduce our proposed approach, starting from the model for the routing module, and describe strategies for route selection that take into account UWB features (power limitation, synchronization, battery limitation, interference, etc.) and coexistence issues. In Section 1.4 we define a routing cost function that incorporates the model of Section 1.3. The approach is analyzed and investigated by simulation as described in Section 1.5. Section 1.6 concludes the chapter.

1.2. Previous work

Research activities related to the introduction of cognition in the routing process have been carried out in the last fifteen years with particular interest to the introduction of learning capabilities in the routing algorithm. In the following we will start our review from earlier works on cognitive routing, that mainly addressed the case of fixed and wired networks, and focused on the optimization of internal network behavior, without considering the problem of interaction with external systems [4–7]. We will then analyze more recent works, where the growing interest for cognitive radios led to the proposal of routing protocols capable of coping with the frequent topology changes due to the channel switching of cognitive radios forming the network [8–11].

In [4] the authors propose the application of computing intelligence to the routing problem, by introducing a set of agents inspired to the behavior of ants in an ant colony. The agents, which can be implemented in the form of probe packets, explore the network in order to collect information on average end-to-end delay, and propagate backward in order to update the intermediate routers according to the collected information.
The authors move from previous work on artificial colonies-based routing and introduce learning capabilities by means of a reinforced learning mechanism based on artifical neural networks. The proposed solution can be summarized as follows:

- An artificial neural network is implemented in each router. The neural network receives as input the probability of selecting each possible next hop towards a given destination and the average trip time towards that destination using each possible next hop, and provides as output the new values of probabilities and estimated trip times to the same destination for each possible next hop;
- At each hop, a forward ant traveling to a given destination selects the next hop by using the artificial neural network;
- When an ant propagates backward from the destination to a previously visited node, it updates the weights of the neural network and the routing table according to the measured trip time to the destination, thus modifying the behaviour of the neural network and the choices of the following ants.

Simulation results reported in [4] show that the introduction of learning capabilities can improve routing performance, leading to a slight increase in throughput and a significant reduction in end-to-end delay.
The approach proposed in [4] for the behavior of a single node can actually be mapped on the cognitive cycle as defined by Mitola. Each node in the network observes the system status by receiving the measurements provided by the ants, and takes decisions according to the observation. Furthermore, both the system status and the impact of previous decisions are taken into account in the learning process, impacting future decisions. Overall, network behavior is thus the result of independent cognitive cycles taking place in each network node.

The concept of cognitive routing is addressed more thoroughly in [5]. In this work the authors move the learning capability from the node to the packet, by introducing the concept of Cognitive Packets. A Cognitive Packet (CP) is divided in four parts: the ID field (for identifying the packet and its class of service), the DATA field (carrying user data), and two special fields related to the cognitive routing algorithm: the Cognitive Map field and the Executable Code field. The Cognitive Map contains a network map, that is, an estimation of the state of the network based on previous information collected by the packet. The Executable Code implements a decision-taking algorithm that operates using the CM field as an input, and a learning algorithm for the update of the CM. Furthermore, the decision-taking and learning algorithms take into account a predefined goal set for the packet, that is a performance metric to be optimized, such as minimum delay or maximum throughput.
Nodes in the network play essentially two roles: a) they provide storing capability in the form of Mailboxes, that can be read or written by Cognitive Packets; b) they execute the Executable Code contained in each received packet.
Whenever a CP is received by a node, the node executes the code stored in the Executable Code field of the packet; the input to the code is constituted of the Cognitive Map stored in the node itself, and the content of the Mailbox in the node. As a result of the code execution any of the following actions can be performed:

- the Cognitive Map in the packet is updated;
- the Mailbox in the node is written;
- the packet is sent on an output link;
- the packet is kept in a buffer waiting for a given condition to be met.

The authors compare the performance of their Cognitive Packet Network with a straightforward shortest path algorithm, and show that even in the case of very simple learning and decision-taking algorithms their approach can improve performance in terms of packet loss and delay. Even larger improvements in network performance can be obtained when more complex learning algorithms, such as neural networks, are implemented in the Executable Code field.
The approach proposed in [5] poses, however, several implementation challenges, in particular in terms of routing overhead due to the code to be stored in each packet. Later evolutions of the approach moved back to a more traditional approach, where the learning and decision-taking code is

stored in the nodes, and its execution is triggered by the arrive of Cognitive Packets [6]. Furthermore, Cognitive Packets only constitute a small fraction of overall packets and do not carry any user data information, leading to a solution similar to the one later proposed in [4], that was described above.

In the original formulation of the CPN approach, the Cognitive Map field poses an overhead issue as well, since the number of observations grows with path length, and thus with the size of the network. In order to solve this issue, a modified version of the protocol was proposed in [7], in order to improve scalability and reduce overhead, making the protocol potentially suitable for wireless networks as well.

In [8, 9] the authors propose a routing metric that models the end-to-end delay by taking into account both the average delay introduced by collisions on a single frequency band and the delay introduced by each channel switch required along the path.

The work presented in [10] addresses the same problem by proposing a solution for spreading the information on the positions of the nodes and the channels available to each node, in order to enable efficient routing. The proposed information exchange protocol, based on a broadacast packet exchange, is however only tested in a very favourable scenario, characterized by an error-free channel and collision-free medium access.

An additional characteristic of cognitive radio networks that may impact routing is the fact that the network can be formed by devices complying to different wireless standards. Furthermore, a network node can potentially support more than one wireless network interface. The routing protocol proposed in [11] deals with this aspect, by introducing a routing metric that models the different characteristics of each radio link available between network nodes. The metric is used to build a routing tree between a base station and wireless nodes in the network.

Channel switching is only one of the possible solutions to allow coexistence between cognitive secondary users and primary users. Ultra Wide Band radio offers an alternative solution: thanks to the huge bandwidth used by the UWB signal and the low power levels allowed by regulation, an UWB signal is in most cases invisible to the primary user. The main problem in routing within an UWB network is thus to cope with the interference caused by primary users. This goal can be aachieved by including the interference generated by such users among the routing criteria. A cognitive routing model that addresses this problem, originally proposed in [1], is illustrated in the following sections.

1.3. Routing strategy

As indicated in section 1.1, our research is framed within the area of UWB ad-hoc and self-organizing networks. As a consequence we assume that the MAC strategy adopted in the network is based on our previously investigated $(UWB)^2$ protocol [12, 13]. The basic hypothesis of $(UWB)^2$ is uncoordinated access in an Aloha-like fashion. The Aloha approach that forms the basis of $(UWB)^2$ was actually voted with a large majority of votes as the medium access strategy for the IEEE 802.15.4a standard, although a CSMA approach is also available for optional operational modes. As regards routing strategy, key issues that must be taken into account in the selection of a multi-hop route can be listed as follows:

- *Synchronization*: the assumption of an uncoordinated MAC protocol leads to a significant synchronization overhead. In particular, control routing packets, such as Route ReQuest and Route ReConstruct packets, introduce the heavier overhead, since synchronization must be acquired between terminals that, in the worst case, are not aware of each other. On the other hand, transmission of data packets over active connections may require lower overhead, since transmitter and receiver preserve at least coarse synchronization between two consecutive packets.
- *Power*: smart management of available power in order to optimize network performance while meeting the emission limits for UWB devices is required. As a consequence, power issues should be paramount in route selection, in order to efficiently make use of available power. The concept of power-aware routing for ad-hoc networks was widely analyzed in past investigation [14, 15]. Figures 1.1 and 1.2 show the impact of using hops vs. power as the routing metric.
- *Multi-User Interference (MUI)*: selecting power-optimized routes, by itself, is not sufficient for guaranteeing the efficient use of power at the network level. The selection of a route in a high density region, in fact, may provoke increased required power to achieve an acceptable Packet Error Rate (PER) on all active links of such a region, due to increased interference, leading thus to inefficient power use. MUI should therefore be taken into account in route selection. This can be achieved by considering network topology, as shown in Figure 1.3 vs. Figure 1.4. Figure 1.3 shows the minimum-energy route, which is likely to cause high interference due to high network density (see for example node 9). Oppositely, Figure 1.4 shows an alternative route that takes into account network

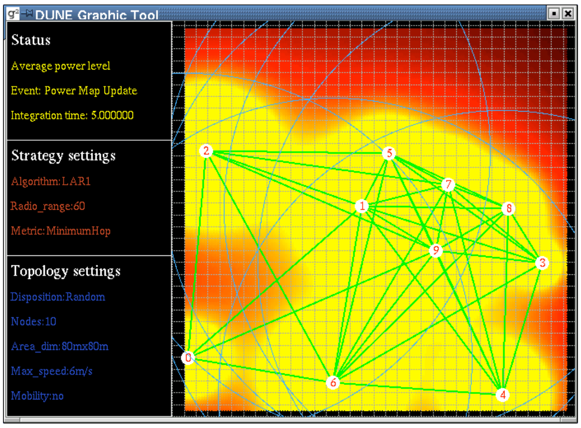

Fig. 1.1. Spatial power distribution in the case of minimum number of hops route selection strategy. Brighter spots on the map correspond to higher average spatial power density levels.

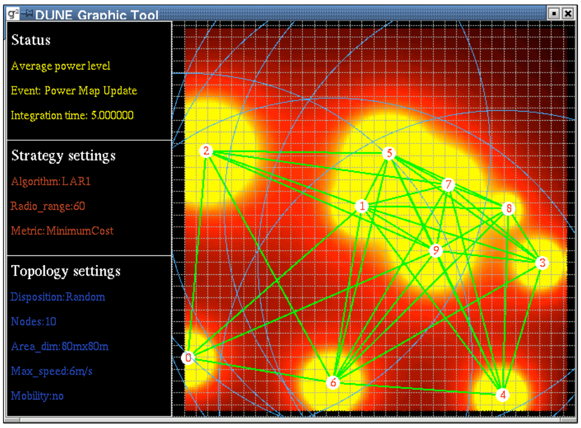

Fig. 1.2. Spatial power distribution in the case of minimum energy route selection strategy. Brighter spots on the map correspond to higher average spatial power density levels. Note that compared to Figure 1.1 this route selection strategy reduces the average spatial power density.

topology, and therefore avoids the high-density region.

- *Link reliability*: node mobility and variable network conditions (due to link set-up and releases, nodes switching on and off) may cause high instability in selected routes, leading to frequent route reconstruction procedures, and thus high overhead. Poor reliability can easily lead to poor

QoS. In order to reduce instability, link reliability should be incorporated in the route selection procedure.

- *Traffic load*: the above criteria may potentially cause a terminal that particularly fits one or more criteria to be more frequently selected than others. For example, a non-mobile terminal may guarantee greater reliability, and may experience therefore heavier traffic, with the consequence of reduced battery autonomy. This negative effect can be avoided if traffic load of each terminal is taken into account in route selection.
- *End-to-end delay*: as observed above, link reliability is crucial for QoS when required, such as in ftp and http transfers. On the other hand, in the case of voice and multimedia traffic having a low end-to-end delay is far more important than correctly delivering all packets. Delay should therefore also be taken into account in route selection, in order to assure acceptable delays for time-sensitive traffic classes.
- *Battery autonomy*: transmission power is not the only source of power consumption in a node, and route selection should also take into account power consumption due to processing in the node, as for example during the receiving action or the execution of code implementing MAC and routing algorithms. Energy efficiency in the selection of the end-to-end path should consider the residual energy in each node, and attribute higher costs to nodes that are running low of energy.
- *Coexistence*: the above criteria refer to an autistic UWB network, and ignore the environment in which the UWB network operates. Due to coexistence, however, in particular with narrowband systems, route selection must be able to adapt to external interference. This is where we introduce a cognitive mechanism in the operating principle of the routing module.

Note that according to the above criteria the route selection process must in some cases integrate trade-offs between opposite requirements. The power minimization component, for example, leads to routes composed by several hops. On the other hand, the end-to-end delay favors routes with few hops.

1.4. Cognitive routing cost function

In this section, we introduce a cognitive routing cost function that is defined as the sum of different sub-costs that in turn take into account each of the routing criteria defined in the previous section. The total cost corre-

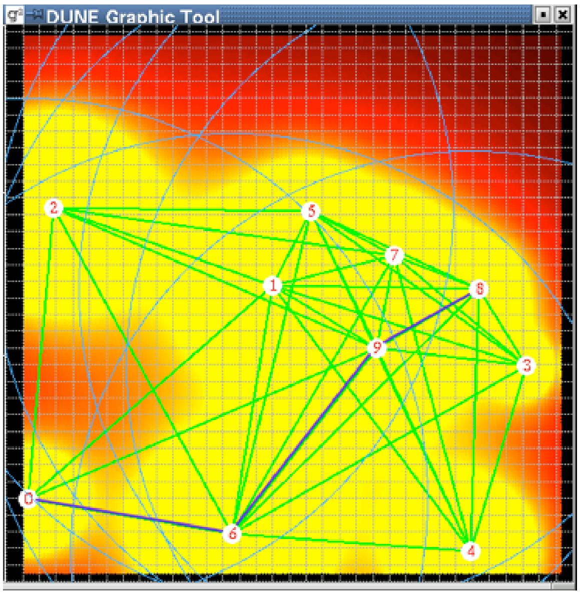

Fig. 1.3. Example of minimum-energy route subject to high interference. The highlighted route between nodes 0 and 8 is potentially subject to high interference, in particular at intermediate node 9.

sponds, therefore, to a linear combination of sub-costs, where each additive component is weighted by a specific sub-cost coefficient.
According to the criteria defined in the previous section, the cost function over a generic link between nodes x and y should account for the following sub-costs: synchronization, transmission power, multi-user interference, reliability, traffic load, delay, autonomy, and coexistence. A general expression for the routing cost function can be thus written as follows:

$$\begin{aligned} Cost\left(x,y\right) = {} & c_{Sync}\left(t\right) \cdot Sync\left(x,y\right) + c_{Power}\left(t\right) \cdot Power\left(x,y\right) + \\ & + c_{MUI}\left(t\right) \cdot MUI\left(x,y\right) + c_{Reliability}\left(t\right) \cdot Reliability\left(x,y\right) + \\ & + c_{Traffic}\left(t\right) \cdot Traffic\left(y\right) + c_{Delay}\left(t\right) \cdot Delay\left(x,y\right) + \\ & + c_{Autonomy}\left(t\right) \cdot Autonomy\left(y\right) + \\ & + c_{Coexistence}\left(t\right) \cdot Coexistence\left(y\right). \end{aligned} \tag{1.1}$$

Note that some terms in Eq.1.1 depend on the status of both transmitter x and receiver y, while others such as the Traffic, Autonomy and Coexistence terms only take into account the status of receiver y. Sub-cost coefficients

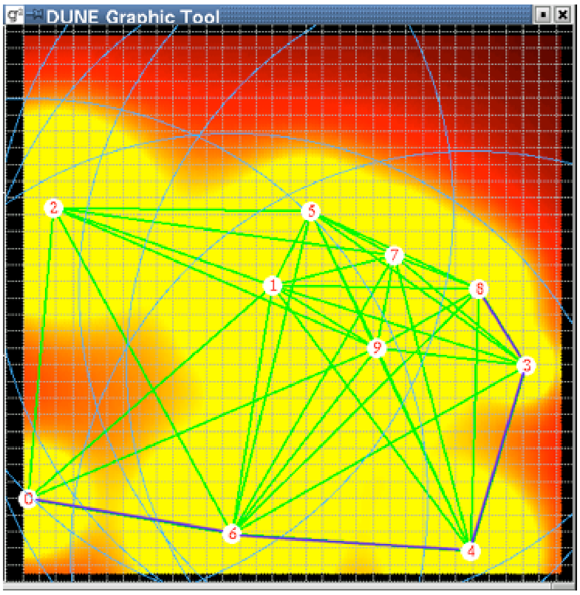

Fig. 1.4. Example of a topology sensitive minimum-energy route between nodes 0 and 8. Note that compared to Figure 1.3 this route avoids highly interfered nodes such as node 9.

are assumed to be dependent upon time t; this assumption wants to account for time-varying properties of the network, such as variable topology, traffic features, and degree of cognition in the nodes.
In the following we analyze and propose a possible way for defining each term of the cost function separately.

1.4.1. *Synchronization term*

This term can be defined as follows:

$$Sync\,(x, y) = \delta\,(x, y)\,, \tag{1.2}$$

where $\delta(x, y)$ is 0 if nodes x and y already share an active connection, and 1 otherwise.
Given the $(UWB)^2$ access protocol, synchronization between transmitter and receiver must be acquired from scratch for all random packets involved in setting up a link.

1.4.2. *Power term*

We define the power term as follows:

$$Power\,(x,y) = \left(\frac{d\,(x,y)}{d_{max}}\right)^{\alpha}, \tag{1.3}$$

where $d(x,y)$ is the distance between x and y, d_{max} is the maximum transmission distance from x as estimated by x that still guarantees a target SNR, and α is the path loss exponent. This term takes into account the power required to transmit over the link between x and y for a given SNR, normalized by the maximum transmit power. SNR characterizing link (x,y) is in fact:

$$\begin{aligned} SNR = \tfrac{P_T(x,y)/A(d(x,y))}{P_N} = \tfrac{P_T(x,y)/(A_0 \cdot d^{\alpha}(x,y))}{P_N} \\ \Rightarrow P_T\,(x,y) = SNR \cdot P_N \cdot (A_0 \cdot d^{\alpha}\,(x,y))\,, \end{aligned} \tag{1.4}$$

where $P_T(x,y)$ is transmission power, $A(d)$ is attenuation over link (x,y) and P_N is noise power. For a target SNR and given bit rate, the transmitted power corresponding to d_{max} is thus:

$$P_{max} = SNR \cdot P_N \cdot (A_0 \cdot d_{max}^{\alpha})\,. \tag{1.5}$$

One has thus:

$$\frac{P_T\,(x,y)}{P_{max}} = \frac{SNR \cdot P_N \cdot A_0 \cdot d^{\alpha}\,(x,y)}{SNR \cdot P_N \cdot A_0 \cdot d_{max}^{\alpha}} = \left(\frac{d\,(x,y)}{d_{max}}\right)^{\alpha}. \tag{1.6}$$

In order to compute the power term the receiver node y must have an estimate of distance $d(x,y)$; this information is expected to be provided by the UWB ranging module. An estimate of P_{max} at node x may also be required except in the case that all terminals have same P_{max}, where an explicit computation of such quantity is not necessary.

1.4.3. *MUI term*

This term takes into account the potential impact of a transmission from x to y on the neighbouring nodes of x.

With regards to MUI, a node x should be avoided if either of the following conditions is met:

(1) x has a large number of neighbours that could be adversely affected by its transmission;

(2) x has a neighbour at very short distance, that would be subject to a strong interference during transmission by x.

Given the ranging capability provided by the UWB physical layer, we propose to use distance information in order to model the impact of x as determined by the two above conditions. A possible way to achieve this goal is to define the MUI term as follows:

$$MUI\,(x,y) = \frac{1}{N_{Neigh}\,(x) - 1} \cdot \sum_{n=1,\, n\neq y}^{N_{Neigh}(x)} \left(1 - \frac{d_{min/y}}{d\,(x,n)}\right)^2, \qquad (1.7)$$

where:

- N_{Neigh} is the number of neighbours known to x;
- n is the generic neighbour, excluding y;
- $d_{min/y}$ is the distance between x and its closest neighbour, excluding y.

The value assumed by the term defined in Eq.1.7 as a function of the number of neighbours and the maximum value of the ratio $d\,(x,n)\,/d_{min/y}$ is shown in Figure 1.5. Note that when both the conditions previously defined are satisfied the MUI term assumes high values, thus discouraging the inclusion of the (x,y) link in the selected route.

1.4.4. *Reliability term*

We measure the reliability of a link (x,y) as the combination of two factors:

- the number of packets exchanged between x and y within a predefined observation interval: the higher is such number, the higher is the expected stability of the link;
- the MUI potentially affecting the intended receiver y.

According to this approach, the reliability term can be defined as follows:

$$\begin{aligned} Reliability\,(x,y) = \frac{1}{2}\Bigg[&\frac{1}{N_{packets}\,(x,y)} + \\ &+ \frac{1}{N_{Neigh}\,(y) - 1} \cdot \sum_{n=1,\, n\neq x}^{N_{Neigh}(y)} \left(1 - \frac{d_{min/x}}{d\,(y,n)}\right)^2\Bigg], \qquad (1.8)\end{aligned}$$

where:

- $N_{packets}(x,y)$ is the number of packets y received from x in the last observation interval;

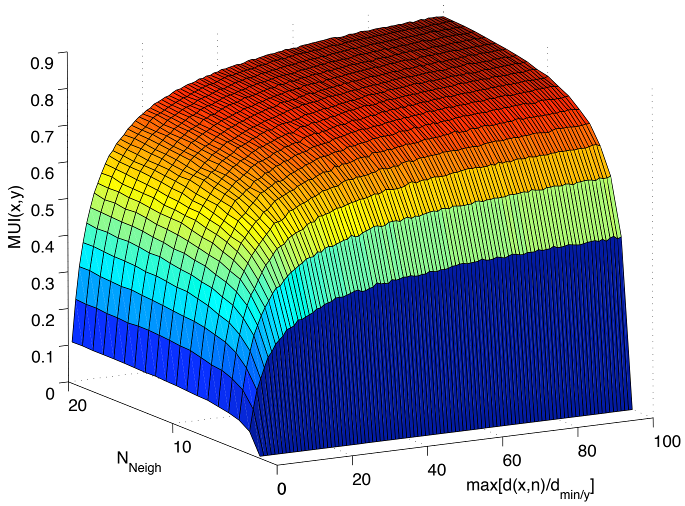

Fig. 1.5. Value assumed by the MUI term for the (x, y) link as a function of the number of neighbours of x,N_{Neigh}, and of the maximum value of the ratio $d(x, n)/d_{min/y}$ between the distance from x to a generic neighbour n and the distance to the closest neighbour excluding y.

- $N_{Neigh}(y)$ is the number of neighbours known to y;
- n is the generic neighbour, excluding x;
- $d_{min/x}$ is the distance between y and its closest neighbour, excluding x.

The stability of the link, expressed by the number of packets that y has received from x at a given time, implicitly takes into account node mobility. Expected MUI also affects reliability and is evaluated as proposed for the MUI term, but with reference to receiver y. As an alternative, y could provide an estimation of future interference based on the interference observed in the past.

1.4.5. *Traffic term*

The analytical expression for this term writes:

$$Traffic\,(y) = \frac{1}{B_{max}\,(y)} \sum_{i=0}^{N_{active}(y)-1} B_i, \tag{1.9}$$

where:

- $B_{max}(y)$ is the maximum overall rate that can be guaranteed by node y;
- B_i is the rate of the i-th active connection involving y;
- $N_{active}(y)$ is the total number of active connections at y.

As anticipated in Section 1.3, this term avoids unfair selection of routes by increasing the cost of routes including nodes already involved in many active connections.

1.4.6. *Delay term*

This term is defined as follows:

$$Delay(x, y) = 1. \tag{1.10}$$

As a first approximation, the end-to-end delay can be considered to be proportional to the number of hops; in this case, this term is constant.

1.4.7. *Autonomy term*

We give the following expression to the autonomy term:

$$Autonomy\,(y) = 1 - \frac{ResidualEnergy\,(y)}{FullEnergy\,(y)}, \tag{1.11}$$

where $FullEnergy(y)$ is the energy available in y when the node is first turned on. $ResidualEnergy(y)$ is the energy that is left at time of evaluation of the term.

1.4.8. *Coexistence term*

The coexistence term can be defined as follows:

$$Coexistence\,(y) = \frac{MeasuredExternalInterference\,(y)}{MaximumInterference\,(y)}. \tag{1.12}$$

Note that the introduction of this term requires that the UWB receiver can measure the level of narrowband interference.

1.5. Simulations

The cognitive routing strategy described in the previous sections was tested by simulation. The routing model was implemented in the framework of the OMNeT++ simulation tool, by combining the routing cost function with the Dijkstra shortest path algorithm. During simulations the computation of the shortest path was carried out by a central node that communicated the path to each node starting a new data connection. The overhead generated by the central cognitive node for the collection of the cost values and the transmission of path information to interested nodes was neglected in the analysis for the sake of simplicity.
The simulation analysis focused on the effect of three terms: end-to-end delay, autonomy, and coexistence. The effect of other terms was analyzed in previous investigations, as described in [16].

1.5.1. *Simulation scenario*

We considered a network of UWB devices basically following IEEE 802.15.4a Task Group specifications, and adopting thus a Time-Hopping Impulse Radio transmission technique [17]. Furthermore, all devices adopted the $(UWB)^2$ MAC protocol [12, 13].
Main simulations settings are presented in Table 1.1.

Table 1.1. Simulation settings.

Parameter	Setting
Number of nodes	50
Area	150 m × 150 m
Network physical topology	Random node positions, averaged on 10 topologies
Channel model	802.15.4a (see [18])
User bit rate R	64 kb/s
Transmission rate	1 Mb/s
Available transmission power	74 μW (FCC limit for 1 GHz bandwidth)
Traffic model	Constant bit rate connections with average duration 15 s
DATA packet length	576 bits (+ 64 bits for Sync trailer)
UWB Interference Model	Pulse Collision (see [19])
Transmission settings	$N_s = 10$, $T_s = 100\ ns$, $T_m = 1\ ns$

1.5.2. *External Interference*

In order to analyze the impact of a cognitive cost function on system performance in the presence of external interferers, we introduced interference sources modeled as wideband interferers.
Each interferer was characterized by an emitted power P_{Tx}, an activity factor a, a transmission bandwidth B_{INT}, and a carrier frequency f_c. An interferer was randomly added or removed from the system every T_{Switch} seconds, in order to take into account variable interference conditions. The interference characteristics in terms of bandwidth and carrier frequency were chosen in order to model a WiMax [20] transmitter at 3.5 GHz, which constitutes at present day one of the most relevant coexistence scenarios for UWB systems [21].
The settings used for generating the interferers are presented in Table 1.2.

Table 1.2. External interferers settings.

Parameter	Setting
P_{Tx}	10 mW
Position	Randomly selected
Activity factor a	Uniform random variable in (0,1)
Carrier frequency f_c	3.5 GHz
Transmission bandwidth B_{INT}	10 MHz
Update time period T_{Switch}	100 s
Initial number of interferers	2

1.5.3. *Cost function settings*

In the simulation we compared three different coefficient sets in the scenario defined in Sections 1.5.1 and 1.5.2. The coefficient sets are presented in Table 1.3. Note that the coefficients of the other terms are set to zero in the investigation presented in this work (see [16] for the analysis on other terms).

Set 1 only takes into account delay in the determination of the best path. Given the definition of the Delay cost term in Section 1.4.6, set 1 leads to the selection of the path characterized by the minimum number of hops.
Set 2 favors the selection of paths minimizing the Autonomy cost (see Section 1.4.7), and aims at maximizing network lifetime.

Table 1.3. Cost function coefficient sets.

Coefficient	Set 1	Set 2	Set 3
C_{Delay}	1	0.0001	0.0001
$C_{Autonomy}$	0	1	0
$C_{Coexistence}$	0	0	1

Set 3 leads to the selection of paths involving nodes suffering external interference in a minor way, thus aiming at the best possible coexistence between UWB and external interferers.

1.5.4. *Simulation results*

Two runs of simulations were carried out.
The first run focused on network performance in presence of external interference. Performance was expressed by throughput and end-to-end delay.
The second run analyzed network lifetime both in presence and absence of external interference. Network lifetime was expressed by the time at which the first node run out of battery from network start-up.
In the first simulation run, Network performance was analyzed for the three coefficient sets defined in Section 1.5.3, in the presence of external interference.
Throughput and end-to-end delay in the three cases are shown in Fig. 1.6 and Fig. 1.7 , respectively. Results highlight that the adoption of a routing cost function that takes into account measured external interference (Set 3) significantly improves both throughput and delay compared to the case where only UWB network internal status is considered in the route selection (Sets 1 and 2).

As discussed in Section 1.3, however, a cost function that takes into account only one specific aspect (e.g. Power, Interference, or Delay) in route selection may lead to unfair energy consumption among terminals. In order to address this issue we analyzed fairness in energy consumption for the three coefficient sets by measuring network lifetime.
Two cases were considered: absence of external interference, and presence of interferers according to the settings of Table 1.2.
Previous work on energy-aware routing suggested that a routing cost function that takes into account the residual autonomy of the nodes leads to high fairness and thus to long lifetime [15]. Results obtained in absence of external interference, as presented in Fig. 1.8, are in agreement with the

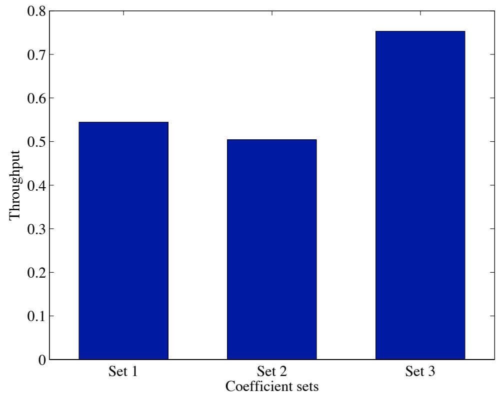

Fig. 1.6. Throughput for the coefficient sets defined in Table 1.3.

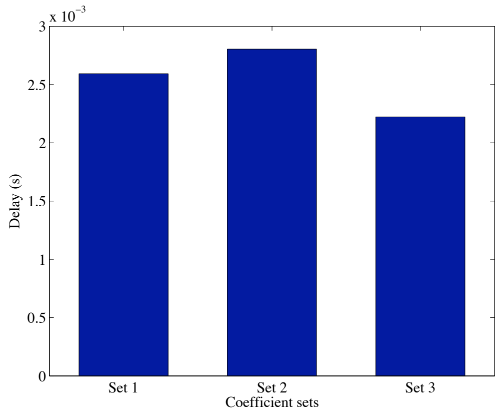

Fig. 1.7. End-to-end delay for the coefficient sets defined in Table 1.3.

above statement.
Set 2, that takes into account battery autonomy in route selection, leads in fact to the longest network lifetime. Note that Set 3, in the absence of interference, performs end-to-end delay minimization, and leads to the same results of set 1.
The introduction of external interference according to the settings in Table 1.2 significantly affected the behavior of the 3 coefficient sets. Results in the presence of interference are presented in Fig. 1.9, showing that Set 2

is no longer the optimal choice in terms of network lifetime. The selection of nodes close to external interference sources causes in fact high power consumption in such nodes due to retransmission attempts, and reduces network lifetime. Set 3 is in this case the best choice, since it guarantees similar network lifetime while providing better network performance.

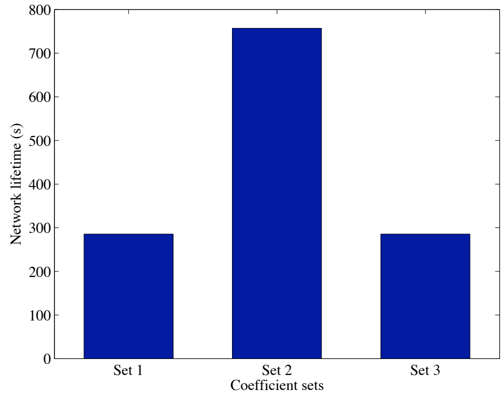

Fig. 1.8. Time of first node death as a function of the coefficient set without external interference.

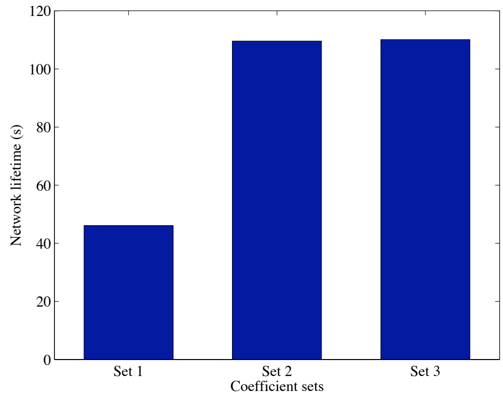

Fig. 1.9. Time of first node death as a function of the coefficient set in presence of external interference.

1.6. Conclusions

In this chapter we analyzed the problem of introducing a cognitive approach in the routing problem. Existing contributions on this topic have been reviewed, identifying the main solutions proposed to this problem for both wired and wireless networks. Next we focused on the Ultra Wide Band case, analyzing the problem optimal choice of a multi-hop route in a network of low data rate UWB terminals of the IEEE 802.15.4a type. Based on this analysis we proposed a cognitive routing cost function that takes into account the status of both the UWB network and the external environment by means of additive cost terms weighted by a set of coefficients.
The adoption of different sets of coefficient allows for a straightforward tuning of the cost function. Different sets can be adopted to support traffic with different characteristics. Non-interactive data traffic, for example, such as ftp transfers, requires a high degree of data integrity but can tolerate high end-to-end delays. The cost function can be customized for this traffic class by increasing the relative weight of the Reliability cost term, while reducing the weight of the Delay term. Oppositely, voice-like traffic can tolerate a relatively high PER, but poses strong constraints on the end-to-end delay. In this case the role of the Reliability and Delay terms are inverted, with the latter term characterized by a much higher relative weight than the former one.
In the results shown in Section 1.5, we focused on a single traffic scenario, characterized by low bit rate connections at constant bit rate, and we investigated the impact of a subset of the cost function terms on network performance and lifetime by means of computer simulations.
Results show that with the introduction of information related to the external interference the routing strategy acquires the capability of adapting network behavior to the external environment, leading to a significant increase in network performance. Furthermore, the reduction of PER and retransmission attempts obtained by taking into account external interference sources in route selection contributes to achieve a fair power consumption among nodes, and thus a long network lifetime.
The proposed cognitive routing approach focuses on a subset of the actions defined in the cognitive cycle: in particular, the algorithm observes the network status, decides by selecting the best route given the observation data and acts by modifying the routing tables of the nodes involved in the path. We foresee that the introduction of a learning capability based on the result of previous decisions can further improve the performance of the

algorithm. A possible solution to introduce such learning capability is to allow network nodes to modify the cost function coefficients on the basis of the impact of previous routing decisions on network performance. In order to do so, however, several challenges must be addressed, including the definition of the feedback mechanisms and of the algorithm for coefficients tuning. Addressing such challenges will be the main subject of our future research activities on this topic.

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