Invited paper at the IEEE International Conference on UWB 2006 (ICUWB2006), September 24 - 27 2006, Boston, Massachusetts, USA

# Cognitive routing in UWB networks

Maria-Gabriella Di Benedetto, *Senior Member, IEEE*, and Luca De Nardis, *Member, IEEE*

*Abstract*— **This paper investigates the effect of introducing cognitive mechanisms in the logic of a wireless network as regards routing. A routing cost function incorporating measurements of the instantaneous behaviour of the external world, as represented for example by current network status in terms of interference suffered by overlaid networks is defined in the framework of IEEE 802.15.4a-like low data rate and low cost networks for mixed indoor/outdoor communications. We simulated a network of nodes and implemented the cognitive approach in the routing module. Network behavior was analyzed in terms of 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.**

*Index Terms*—**Cognitive, Routing, UWB**

## I. Introduction

DRIVING the design of communication systems 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 is currently one of the major challenges for communication engineers.

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" [1] 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. The final goal remains to form wireless networks that are capable of cooperatively coexisting in a given geographical area.

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 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 introduction of the cognitive principle in the logic of a wireless network as regards for example resource management and routing 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.

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 consider 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 the 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. Current activities within 802.15.4a focus on the definition of the Medium Access Control (MAC) layer [3].

The paper is organized as follows. In Section II we introduce 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 III we define a routing cost function that incorporates the model of section II. The approach is analyzed and investigated by simulation as described in Section IV. Section V concludes the paper.

## II. Routing Strategies

As indicated above, 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 the assumptions of our previously investigated $(UWB)^2$ protocol [3]. 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

Manuscript received July 9, 2006. This work was supported in part by the European Commission in the framework of the Integrated Projects N. 511766 LIAISON (LocatIon bAsed servIceS for the enhancement of wOrking enviroNment) and N. 506897 PULSERS (Pervasive Ultra-wideband Low Spectral Energy Radio Systems), and by STMicroelectronics Italy in the framework of the research contract "UWB Ranging and Positioning in Radio Communication Systems."

Both authors are with the Info-Com Department, School of Engineering, University of Rome La Sapienza, Via Eudossiana 18, 00184, Rome, Italy.

Luca De Nardis is currently a post-doc researcher at the Berkeley Wireless Research Center, EECS Department, University of California at Berkeley.

E-mail addresses: [dibenedetto, lucadn]@newyork.ing.uniroma1.it.

CSMA approach appears to be still on-track for optional operational modes.

As regards routing strategies, 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 likely 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 investigated ([5], [6]).
– *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 the network topology, as shown in Fig. 1 vs. Fig. 2. Fig. 1 shows the minimum-energy route, which is likely to cause high interference due to high network density (see nodes for example node 9). Oppositely, Fig. 2 shows an alternative route that takes into account network 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.

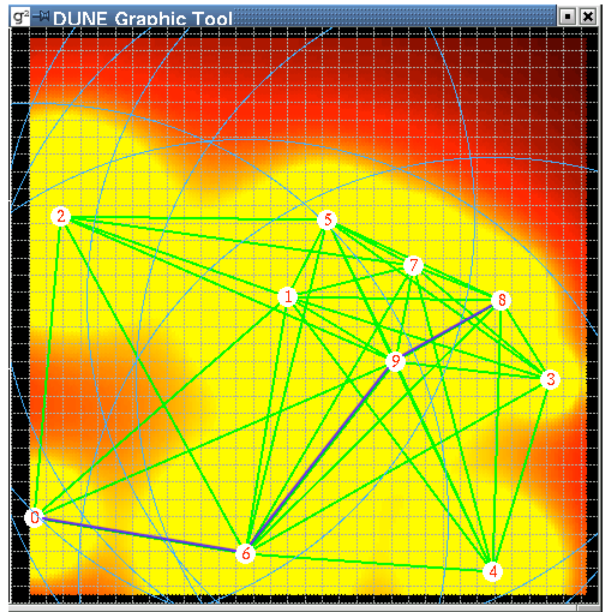


Fig. 1. Example of minimum-energy route between nodes 0 and 8, subject to high interference, especially in 9.

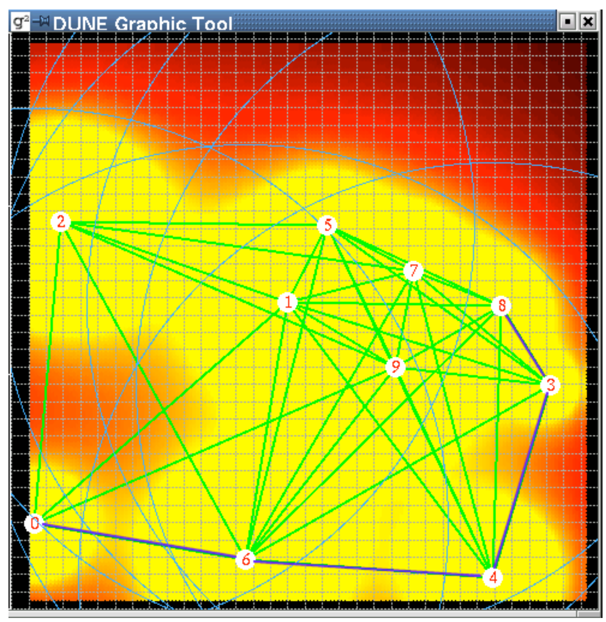


Fig. 2. Example of a topology sensitive minimum-energy route between nodes 0 and 8. Note that compared to Fig.1 this route avoids highly interfered nodes such as node 9.

– *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, due for example in the receiving action or in algorithms implementation. 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.

## III. 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 corresponds, 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:

$$\begin{aligned} UWB_{Cost}(x,y) &= c_{Sync}(t)\cdot Sync(x,y) + c_{Power}(t)\cdot Power(x,y) + \\ &+ c_{MUI}\cdot MUI(x,y) + c_{Reliability}(t)\cdot Reliability(x,y) + \\ &+ c_{Traffic}(t)\cdot Traffic(y) + c_{Delay}(t)\cdot Delay(x,y) + \\ &+ c_{Autonomy}(t)\cdot Autonomy(y) + c_{Coexistence}(t)\cdot Coexistence(y) \end{aligned} \tag{1}$$

Note that some terms in Eq (1) depend on the status of both transmitter and receiver $x$ and $y$, while others such as the Traffic, Autonomy and Coexistence terms only take into account the status of receiver $y$. Sub-cost coefficients 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.

### A. Synchronization term

This term can be defined as follows:

$$Sync(x,y) = \delta(x,y) \tag{2}$$

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.

### B. Power term

We define the power term as follows:

$$Power(x,y) = \left(\frac{d(x,y)}{d_{\max}}\right)^{\alpha} \tag{3}$$

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 $\alpha$ 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:

$$\begin{aligned} SNR &= \frac{P_T(x,y)\big/A(d(x,y))}{P_N} = \frac{P_T(x,y)\big/\left(A_0\cdot d^{\alpha}(x,y)\right)}{P_N} \\ &\Rightarrow P_T(x,y) = SNR\cdot P_N\cdot\left(A_0\cdot d^{\alpha}(x,y)\right) \end{aligned} \tag{4}$$

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:

$$P_{\max} = SNR\cdot P_N\cdot\left(A_0\cdot d_{\max}^{\alpha}\right) \tag{5}$$

One has thus:

$$\frac{P_T(x,y)}{P_{\max}} = \frac{SNR\cdot P_N\cdot A_0\cdot d^{\alpha}(x,y)}{SNR\cdot P_N\cdot A_0\cdot d_{\max}^{\alpha}} = \left(\frac{d(x,y)}{d_{\max}}\right)^{\alpha} \tag{6}$$

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.

### C. MUI term

Analytically, an estimate of the amount of MUI generated by the transmitter can be expressed as follows:

$$MUI(x,y) = \frac{1}{N_{neighbours}(x)-1}\cdot\sum_{n=0,\,n\neq y}^{N_{neighbours}(x)-1}\left(1-\frac{d_{min/y}}{d(x,n)}\right)^2 \tag{7}$$

where:

– $N_{neighbours}(x)$ 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 $y$.

In a more general approach, one can consider that the terminal measures the amount of MUI and reacts accordingly.

### D. Reliability term

We define the reliability term as follows:

$$Rel(x,y) = \frac{1}{2}\left[\frac{1}{N_{packets}(x,y)}\right] + \frac{1}{2}\left[\frac{1}{N_{neighbours}(y)-1}\cdot\sum_{n=0,\, n\neq x}^{N_{neighbours}(y)-1}\left(1-\frac{d_{min/x}}{d(y,n)}\right)^2\right] \tag{8}$$

where:

- $N_{packets}(x,y)$ is the number of packets $y$ received from $x$ in the last observation interval;
- $N_{neighbours}(y)$ 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 in previous section, but with reference to receiver $y$.

### E. Traffic term

The analytical expression for this term writes:

$$Traffic(y) = \frac{1}{B_{max}(y)}\sum_{i=0}^{N_{active}(y)-1} B_i \tag{9}$$

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

### F. Delay term

This term is defined as follows:

$$Delay(x,y) = 1 \tag{10}$$

To 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.

### G. Autonomy term

We give the following expression to the autonomy term:

$$Autonomy(y) = 1 - \frac{ResidualEnergy(y)}{FullEnergy(y)} \tag{11}$$

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.

### H. Coexistence term

The coexistence term can be defined as follows:

$$Coexistence(y) = \frac{MeasuredExternalInterference(y)}{MaximumInterference(y)} \tag{12}$$

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

## IV. Simulations

In the simulation analysis we implemented the model described above, focusing 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 [7].

### A. 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 [8].

Main simulations settings are presented in Table I.

TABLE I
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 [9]) |
| User bit rate R | 64 kb/s |
| Transmission rate | 1 Mb/s |
| Available transmission power | 74 μW (FCC limit for Bandwidth ≅ 1 GHz) |
| 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 [10]) |
| Transmission settings | $N_s = 10$, $T_s = 100$ ns, $T_m = 1$ ns |

All devices adopt the $(UWB)^2$ MAC protocol [3].

### B. 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 in the ISM band.

Each interferer was characterized by an emitted power $P_{Tx}$, an activity factor $a$, a transmission bandwidth $B_{ISM}$, and a carrier frequency $f_c$. An interferer was randomly added or removed from the system every $T_{Int}$ seconds, in order to take into account variable interference conditions.

The settings used for generating the interferers are presented in Table II.

TABLE II
EXTERNAL INTERFERERS SETTINGS

| Parameter | Setting |
|---|---|
| $P_{Tx}$ | 10 mW |
| Position | Randomly selected |
| Activity factor $a$ | Uniform random variable in (0,1) |
| Carrier frequency $f_c$ | 2.4 GHz |
| Transmission bandwidth $B_{ISM}$ | 11 MHz |
| Update time period $T_{Int}$ | 100 s |
| Initial number of interferers | 2 |

### *C. Cost function settings*

In the simulation we compared three different coefficient sets in the scenario defined in sections IV.A and IV.B. The coefficient sets are presented in Table III. Note that the coefficients of the other terms are set to zero in the investigation presented in this paper (see [7] for the analysis on other terms).

TABLE III
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 1 only takes into account delay in the determination of the best path. Given the definition of the Delay cost term in Section III.F, 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, and aims at maximizing network lifetime.

Set 3 leads to the selection of paths involving nodes suffering external interference in a minor way.

### *D. Simulation results*

Two runs of simulations are described. The first focuses on network performance, expressed by throughput and end-to-end delay, and the second on network lifetime, expressed by the time at which the first node runs out of battery from network start-up.

Network performance was analyzed for the three coefficient sets defined in Section IV.C, in the presence of external interference.

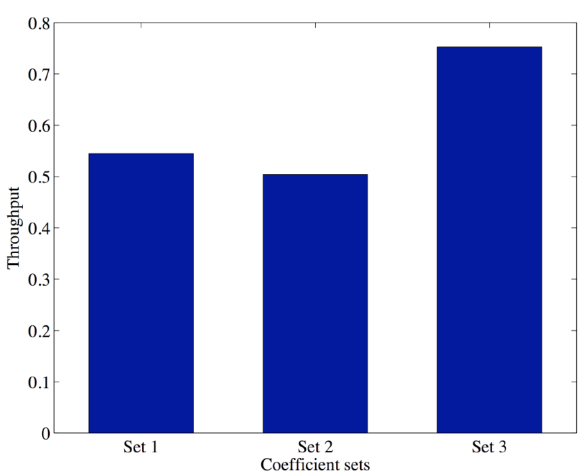


Fig. 3. Throughput for the coefficient sets defined in Table III.

Throughput and end-to-end delay in the three cases are shown in Fig. 3 and Fig. 4, 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 II, 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 II.

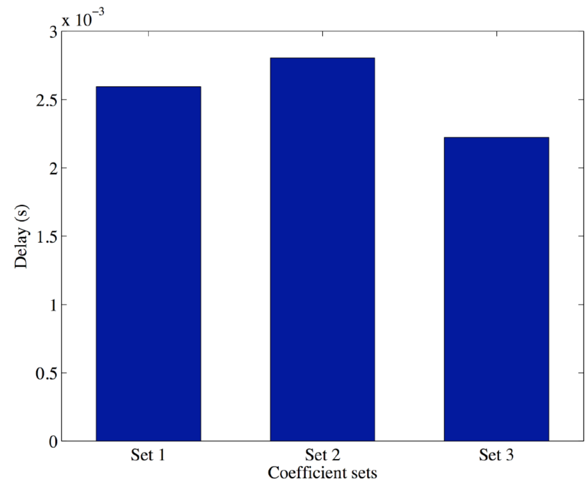


Fig. 4. End-to-end delay for the coefficient sets defined in Table III.

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 [6].

Results obtained in absence of external interference, as presented in Fig. 5, are in agreement with the above statement.

The coefficient 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 II significantly affected the behavior of the 3 coefficient sets. Results in the presence of interference are presented in Fig. 6, showing that coefficient set 2 ceases to be 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.

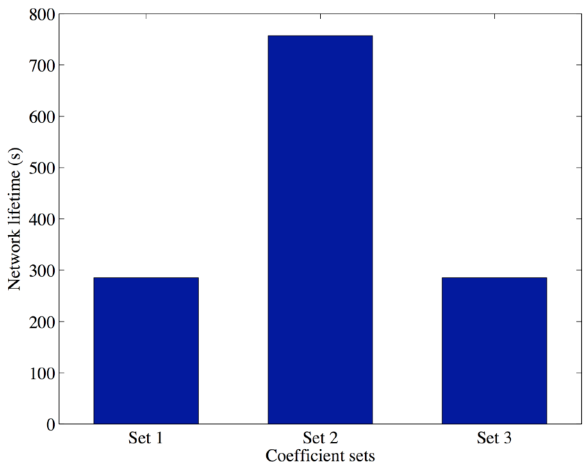


Fig. 5. Time of first node death as a function of the coefficient set without external interference.

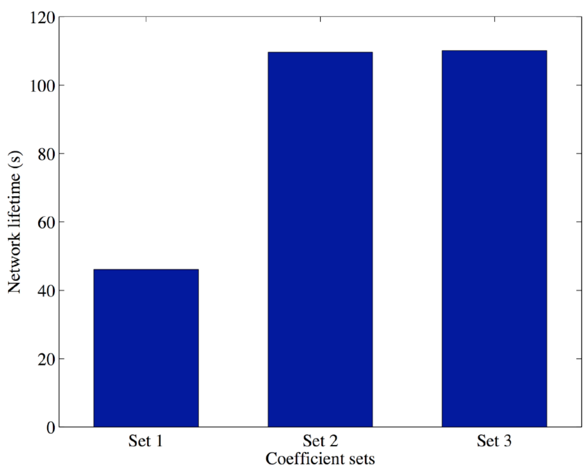


Fig. 6. Time of first node death as a function of the coefficient set in presence of external interference.

## V. Discussion and Conclusions

In this work we analyzed the problem of 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 this work, 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.

## References

[1] J. Mitola and G. Q. Maguire, “Cognitive radio: Making software radios more personal,” IEEE Personal Communications, vol. 6, no. 4, pp. 13 – 18, August 1999.

[2] IEEE 802.15.TG4a web page, available at: http://www.ieee802.org/15/pub/TG4a.html.

[3] L. De Nardis and G. M. Maggio, “Low data rate UWB networks,” in *Ultra Wideband Wireless Communications*, John Wiley & Sons, Inc. (May 2006).

[4] M.-G. Di Benedetto, L. De Nardis, M. Junk and G. Giancola, “$(UWB)^2$: Uncoordinated, Wireless, Baseborn medium access for UWB communication networks,” MONET: Special Issue on WLAN optimization at the MAC and network levels, vol. 5, no. 10, pp. 663 – 674, October 2005.

[5] V. Rodoplu and T. H.-Y. Meng, “Minimum Energy Mobile Wireless Networks,” IEEE Journal on Selected Areas in Communications, vol. 17, no. 8, pp. 1333 – 1344, August 1999.

[6] C.-K. Toh, “Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks,” IEEE Communications Magazine, vol. 39, no. 6, pp. 138 – 147, June 2001.

[7] L. De Nardis, M.-G. Di Benedetto and S. Falco, “Higher layer issues, Ad-Hoc and Sensor Networks,” in *UWB Communications Systems - A Comprehensive Overview*, Hindawi Publishing Corporation, 2006.

[8] M.-G. Di Benedetto and G. Giancola, *Understanding Ultra Wide Band Radio fundamentals*, Prentice Hall, 2004.

[9] IEEE 802.15.4a Channel Model Final Report, Rev.1 (November 2004), available at: ftp://ieee:wireless@ftp.802wirelessworld.com/15/04/15-04-0662-00-004a-channel-model-final-report-r1.pdf.

[10] G. Giancola and M.-G. Di Benedetto, “A Novel Approach for estimating Multi User Interference in Impulse Radio UWB Networks: the Pulse Collision model,” accepted for publication in EURASIP Signal Processing Journal, Special Issue on Signal Processing in UWB Communications (2006).