Cognition in routing for low rate UWB networks

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***Abstract*— This paper investigates the effect of introducing cognitive mechanisms in the routing module of a wireless network. Previous work on the introduction of cognition in the routing function is described, and a routing cost function that incorporates measurements of internal network status and instantaneous behavior of external world is proposed.**

The cost function is analyzed by simulation in a network of IEEE 802.15.4a-like devices for low data rate mixed indoor/outdoor communications. The analysis aims at determining the impact of MUI modeling on network performance. Results indicate that MUI-awareness, as provided by the proposed cognitive cost function, may improve network lifetime.

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

I. 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. Moving from the original 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, the design goal is the definition a network of smart devices that must be capable of efficiently coexist in a given geographical area by using cooperation.

This investigation focuses on introducing the cognitive principle in the routing function. The proposed routing strategy incorporates measurements of the instantaneous behavior of external world, and extends previous work presented in [2].

The framework that we consider for our research refers to low data rate and low cost networks for mixed indoor/outdoor communications compliant to the IEEE 802.15.4a standard [3]. The standard foresees the adoption of an Impulse Radio Ultra Wide Band (IR-UWB) physical layer, capable of providing the accurate ranging information required for accurate positioning; furthermore, a simplified Medium Access Control based on Aloha is introduced in the standard, taking advantage of the robustness of UWB to Multi User Interference (MUI) [4].

The paper is organized as follows. Section II presents an overview of previous work focusing on the introduction of cognition at the routing layer. Section III reviews the cognitive routing strategy origin ally proposed in [2], and presents the new version of the MUI term that is analyzed in this work. Section IV describes the simulation environment and the model adopted for evaluating the interference in the considered UWB low rate network, and presents simulation results. Section V draws conclusions.

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II. 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 towards the introduction of learning capabilities in the routing algorithm.

Earlier work on cognitive routing 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. Proposed solutions relied on probe packets that explore the network in order to collect information on average delay, and propagate the collected information backward in order to update the intermediate routers, enabling learning capability in routing [5], [6].

In light of the growing interest for cognitive radios, more recent work 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. As an example, in [7], [8] authors define 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.

III. Cognitive routing strategy and cost function

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 characteristics of our previously investigated $(UWB)^2$ protocol [9]. The Aloha approach that forms the basis of $(UWB)^2$ was actually selected for the 802.15.4a standard.

As regards routing strategies, key issues that must be taken into account in the selection of a multi-hop route were analyzed in [2], and can be listed as follows: *Synchronization*, *Power, Multi-User Interference (MUI)*, *Link reliability, Traffic load*, *End-to-end delay*, *Battery autonomy*, *Coexistence*.

According to the above criteria, a cognitive routing cost function defined as the sum of different sub-costs was also proposed in [2]. The expression for the routing cost function can be written as follows:

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

A possible way for defining each term of the cost function separately was proposed in [2]. In the following we only introduce the two terms that are considered in this investigation, that is the *Delay* and *MUI* terms.

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A. Delay term

To a first approximation, the end-to-end delay can be considered to be proportional to the number of hops. The term is thus defined as follows:

$$Delay(x,y) = 1. \tag{2}$$

B. MUI term

This term takes into account the potential impact of a transmission from x to y on the neighbors 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 neighbors that could be adversely affected by its transmission;
2. x has a neighbor 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 proposed in [2] to use distance information in order to model the impact of x as determined by the two above conditions.

Building on the above approach, we propose here a refined MUI term that includes both distance and traffic activity of nodes. The new term is defined as follows:

$$MUI(x,y) = \frac{1}{N_{aNeighs}(x)} \sum_{n=0,\, n\neq y}^{N_{aNeighs}(x)-1} \frac{C(n)}{maxC}\left(1 - \frac{d(x,n)}{d_{max/y}}\right)^2 \tag{3}$$

where:

- $N_{aNeighs}(x)$ is the number of active neighbors of x, that is neighbors that are involved in at least a data connection;
- n is the generic active neighbor, excluding y
- $C(n)$ is the number of data connections actually sustained by node n;
- $maxC$ is the maximum number of data connections a node can join simultaneously;
- $d(x,n)$ is the distance between x and n;
- $d_{max/y}$ is the maximum distance between x and a neighbor, excluding y.

The value assumed by the term defined in Eq. (3) as a function of the number of neighbors and the maximum value of the ratio $d_{max/y}/d(x,n)$ is shown in Fig. 1 for the case $C(n) = maxC$ for all n.

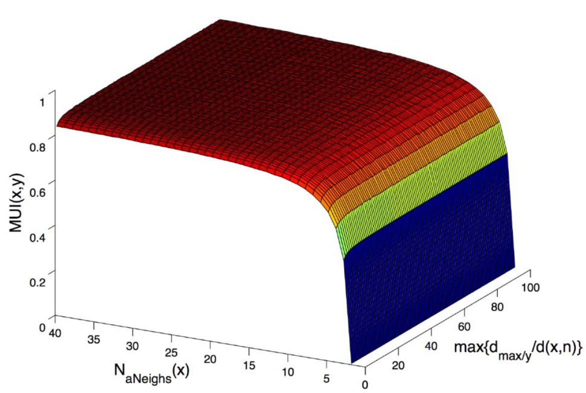

Fig. 1. Value assumed by the MUI term for the (x, y) link as a function of the number of neighbors of x, N_{Neigh}, and of the maximum value of the ratio $d_{man/y}/d(x,n)$ between the distance from x to the furthest neighbor excluding y and the distance to a generic neighbor n for the case $C(n) = maxC$ for all n.

IV. Simulations

In the simulation analysis we implemented the model described above, focusing on the effect of the *Delay* and *MUI* terms. The effect of other terms was analyzed in previous investigations, as described in [2], [10].

A. Simulation environment

Simulations were carried out in the framework of the OMNeT++ simulation environment [11]. A centralized module implementing the Dijkstra routing algorithm ([12]) determined the best path for each connection request, according to the considered routing cost function.

B. Interference modeling and evaluation

Interference modeling and evaluation is a key issue in the analysis of a MUI-aware strategy, and more in general in performance evaluation of any algorithm and protocol designed for wireless networks. In our simulations, we adopted the Pulse Collision interference model that was proved to be accurate in evaluating the impact of MUI on bit error rate in low rate UWB networks [13].

The model was integrated in the simulator as follows. Whenever a node R attempts to receive a packet of duration T, each other packet partially or totally overlapping with the useful one is detected at real time by the interference module. Note that all packets transmitted in the network are taken into account independently from their expected received power at the position of R, thus avoiding the introduction of a predefined transmission range. In order to keep the simulator complexity reasonable, no distinction is made between partial and total overlapping: all packets that share even a very short airtime with the useful packet are assumed to be present for the whole time T and are counted in determining the total number of overlapping packets N_{int}. An example of the evaluation of N_{int} is presented in Fig. 2.

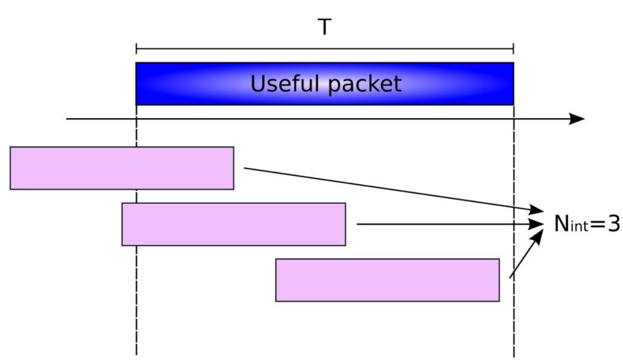

Fig. 2. Example of evaluation of the number of interfering packets for interference modeling

N_{int} is then passed as an input to the module implementing the Pulse Collision model, together with the received power for each packet at the position of node R. This information is used to evaluate the average BER for the bits forming the useful packet by using the analytical formulation described in [13], and a decision on whether accept or discard the packet is taken, under the assumption of no FEC capability.

C. Simulation settings

In each simulation run nodes were randomly placed in a square area, and random connection requests were generated between network nodes. Each request was characterized as a

Constant Bit Rate connection of random duration between random source and destination. Results were averaged over 10 runs for each setting.

All devices adopted the $(UWB)^2$ MAC protocol [9] mentioned in Section III, for medium access.

Main simulation settings are presented in Table I.

TABLE I
SIMULATION SETTINGS

Parameter	Setting
Number of nodes	40
Area	200 m × 200 m
Network topology	Random node positions
Channel model	802.15.4a
User bit rate R	20 kb/s
Transmission rate	1 Mb/s
Transmission power	36.5 µW
Traffic model	CBR with duration in the interval [5-20] s
DATA packet length	320 bits (+ 64 bits for Sync trailer)
Interference Model	Pulse Collision (see [13])

D. Simulation results

The *Delay* and *MUI* minimization strategies were compared in terms of end-to-end throughput and network lifetime, expressed by the time at which the first node runs out of battery from network start-up. In order to better address the impact of the MUI-aware routing strategy on network performance, the average number of hops and the Packet Error Rate were measured as well.

End-to-end throughput measured for the two strategies is presented in Fig. 3.

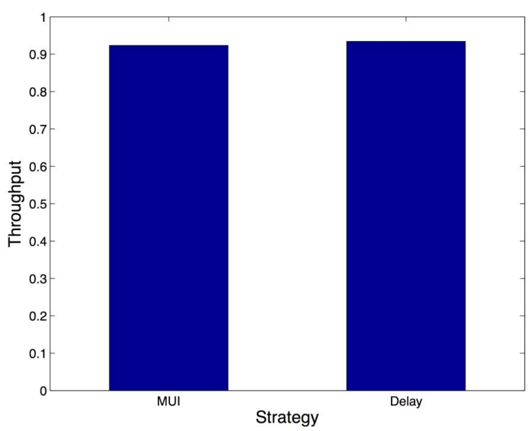

Fig. 3. Throughput for the MUI vs. Delay routing strategies.

Results highlight that the adoption of a routing cost function that takes into account the impact of MUI does not lead to an advantage in terms of throughput. In order to better understand the reason for such result, Packet Error Rate and average number of hops per connection were monitored as well during simulations. Simulation results for the two parameters are presented in Fig. 4 and Fig. 5, respectively.

Fig. 4 shows that the introduction of a MUI-aware approach has indeed a positive impact on the PER, leading to a lower probability of packet discarding. The advantage introduced by the MUI-aware strategy is however compensated by the fact that this strategy also leads to a larger average number of hops compared to Delay minimization, as shown in Fig. 5. It should be noted that, given the delay model adopted in this work, minimizing the end-to-end delay corresponds to minimizing the average number of hops as well.

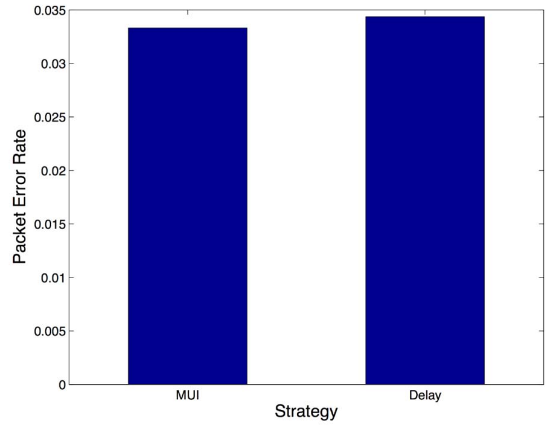

Fig. 4. Packet Error Rate for the MUI vs. Delay routing strategies.

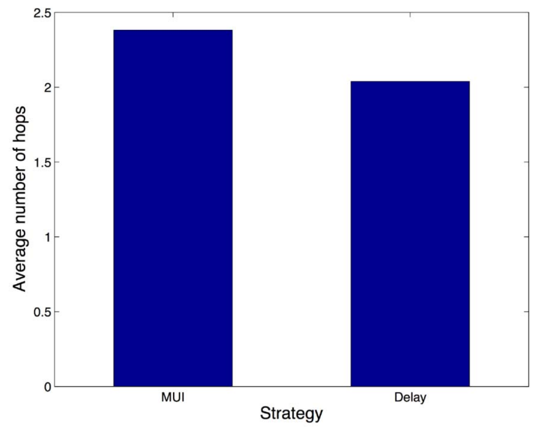

Fig. 5. Average number of hops for the MUI vs. Delay routing strategies.

Simulation results indicate however that the introduction of MUI-awareness does have a positive effect on network lifetime, as shown in Fig. 6. Fig. 6 highlights that the adoption of a MUI-aware coefficient set leads to a longer network lifetime, thanks to a more uniform distribution of traffic among network nodes. This result further confirms that the selection of minimum-hop routes does not lead to a fair use of node energy, in accordance to the results in [2], [10].

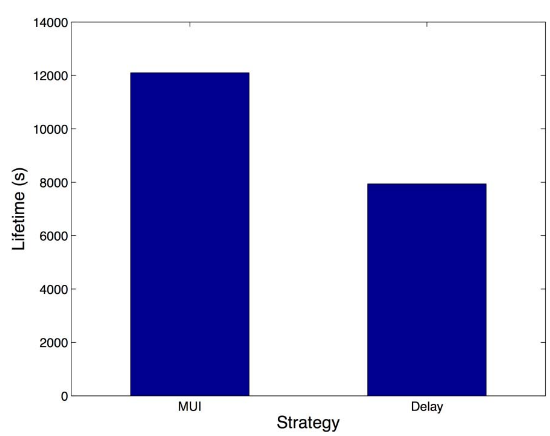

Fig. 6. Network lifetime for the MUI vs. Delay routing strategies.

V. Conclusions and Future Work

In this paper 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. Moving from the work started in [2], we focused on the impact of the MUI term on network performance in a low rate traffic scenario, by measuring end-to-end throughput and network lifetime by means of computer simulations.

Results show that the adoption of a MUI-aware strategy does not necessarily lead to an increase in end-to-end throughput, as the reduction in Packet Error Rate on the single hop is compensated by the increase in average number of hops required for selecting low interference routes. Further research is required to understand under what traffic and topology conditions a MUI-aware strategy can significantly improve throughput. Determining such conditions will be the subject of future work.

Results presented in this work also indicate that the adoption of a MUI-aware routing function has a strong positive effect on network lifetime, almost doubling the time before the first network node expires.

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