Cognitive routing models in UWB networks
(invited paper)

Maria-Gabriella Di Benedetto, *Senior Member, IEEE*, and Luca De Nardis, *Member, IEEE*
INFOCOM Department
School of Engineering, University of Rome La Sapienza
Rome, Italy
{dibenedetto, lucadn}@newyork.ing.uniroma1.it

***Abstract*— This paper investigates the effect of introducing cognitive mechanisms in the routing module of a wireless network. A routing cost function that incorporates measurements of both internal network status and instantaneous behavior of external world is described. The proposed cost function is analyzed by simulation in the framework of IEEE 802.15.4a-like low data rate and low cost networks for mixed indoor/outdoor communications. The analysis focuses on the impact of MUI modeling on network performance. Results indicate that MUI-awareness, as provided by the proposed cognitive cost function, may improve network performance in terms of network lifetime. Based on this analysis, a mechanism for learning from previous routing decisions and adapting the routing cost function to MUI conditions is introduced.**

***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 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 modeled and analyzed as one entity in order to optimize the design of network functions such as resource management and routing.

This investigation focuses on introducing the cognitive principle in the logic of a wireless network as regards routing. The proposed routing function incorporates measurements of the instantaneous behavior of external world, as represented for example by current network status in terms of interference suffered by the overlaid network, 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 investigated within the IEEE 802.15.4a Task Group. The activities within the 802.15.4a Task Group led to the definition of the IEEE 802.5.4a standard in mid-2007 [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. In Section II we review previous work on the cognitive routing problem, and provide a description of the main contributions on this topic. Section III introduces the model for the routing module, i.e. the relevant criteria for route selection (power limitation, battery limitation, synchronization, interference, coexistence, etc.), that extend those presented in [2]. Next, a routing cost function that takes into account such criteria is introduced. The approach is analyzed and investigated by simulation as described in Section IV. Section V concludes the paper.

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 to the introduction of learning capabilities in the routing algorithm. In the following, we start our review from earlier work 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 [5]-[8]. We then analyze more recent work, 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 [9]-[12].

In [5] 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

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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 artificial 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 behavior of the neural network and the choices of the following ants.

Simulation results reported in [5] 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 [5] for the behavior of a single node can actually be mapped on the cognitive cycle as defined by J. Mitola [1]. 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 [6]. 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),
- the Cognitive Map field,
- the Executable Code field.

The two latter fields are related to the cognitive routing algorithm. 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 [6] 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 [7]. 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 [5], 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 [8], in order to improve scalability and reduce overhead, making the protocol potentially suitable for wireless networks as well.

In [9], [10] 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 [11] 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 broadcast packet exchange, is however only tested in a very favorable 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

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routing protocol proposed in [12] 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 achieved by including the interference generated by such users among the routing criteria. A cognitive routing model that addresses this problem, evolved from the one originally proposed in [2], is illustrated in the following sections.

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 assumptions of our previously investigated $(\mathrm{UWB})^2$ protocol [13]. The basic hypothesis of $(\mathrm{UWB})^2$ is uncoordinated access in an ALOHA like fashion. The Aloha approach that forms the basis of $(\mathrm{UWB})^2$ 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 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:

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

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 accounts for time-varying properties of the network, such as variable topology, traffic features, and degree of cognition in the nodes.

In the following we 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 $(\mathrm{UWB})^2$ 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

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 ([14], [15]).

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 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. 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 $d_{\max}$ can be obtained from the value of the maximum transmit power $P_{\max}$ at node x; in the case that all terminals have same $P_{\max}$, an explicit computation of such quantity is not necessary.

C. 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 this approach, we define here a refined MUI term that includes both distance and traffic activity of nodes. The new term is defined as follows:

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

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.
- $d_{max/y}$ is the distance between x and its furthest neighbor, excluding y.
- $d(x,n)$ is the distance between x and n.

D. *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 term is defined as follows:

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

where:

- $N_{packets}(x,y)$ is the number of packets y received from x in the last observation interval;
- $N_{aNeighs}(y)$ is the number of active neighbors of node y;
- n is the generic active neighbor, excluding x;
- $d_{max/x}$ is the distance between y and its furthest neighbor, 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 pointed out in [2], 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 the two terms: end-to-end delay and MUI. The effect of other terms was analyzed in previous investigations, as described in [2], [16].

A. *Simulation scenario*

We considered a network of UWB devices following IEEE 802.15.4a specifications, and adopting thus a Time-Hopping Impulse Radio transmission technique [17].

Main simulations 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 (see [18])
User bit rate R	20 kb/s
Transmission rate	1 Mb/s
Transmission power	36.5 µW
Traffic model	CBR connections with random uniform duration in the interval [5-20] s
DATA packet length	320 bits (+ 64 bits for Sync trailer)
Interference Model	Pulse Collision (see [19])
Transmission settings	$N_s = 10$, $T_s = 100$ ns, $T_m = 1$ ns

All devices adopt the $(UWB)^2$ MAC protocol [13].

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B. *Cost function settings*

We compared two different coefficient sets in the scenario defined in Section IV.A. The coefficient sets are presented in Table II. Note that the coefficients of the other terms are set to zero in the investigation presented in this paper (see [2], [16] for the analysis on other terms).

TABLE II. COEFFICIENT SETS

Coefficient	**Set 1**	**Set 2**
C_{Delay}	1	0.0001
C_{MUI}	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 MUI cost, and aims at reducing the impact of MUI on network performance.

C. *Simulation results*

The two coefficient sets defined in Section IV.B 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. The coefficient sets were compared under three different traffic scenarios: a Low Traffic scenario, characterized by an average time T_{req} between two connection requests set to T_{req}=20 s, a Medium Traffic scenario (T_{req}=10 s), and a High Traffic scenario (T_{req}=5 s).

End-to-end throughput measured for the two coefficient sets in the three scenarios is presented in Fig. 1.

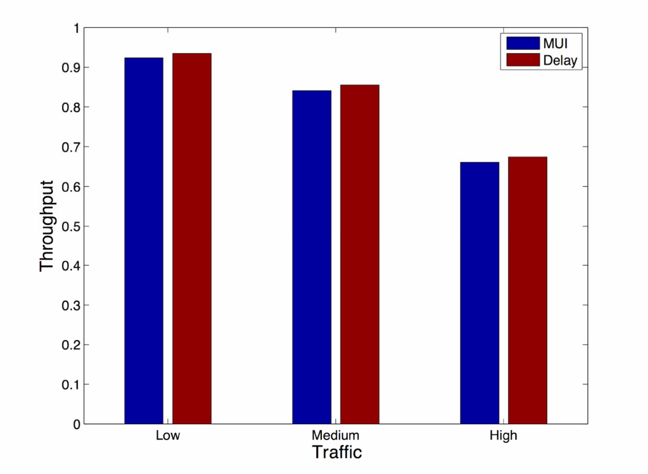

Fig. 1. Throughput for the coefficient sets defined in Table II.

Results highlight that the adoption of a routing cost function that takes into account the impact of MUI (Set 2) does not lead to an advantage in terms of throughput. This result can be explained by observing that the UWB physical layer considered in the simulation scenario provides a high robustness to MUI. As a consequence, MUI is not the main source of packet loss.

It should be noted however that the introduction of MUI awareness does have a positive effect on Packet Error Rate (PER): simulation results indicate in fact that Set 2 leads to a slightly lower PER than Set 1, as shown in Fig. 2.

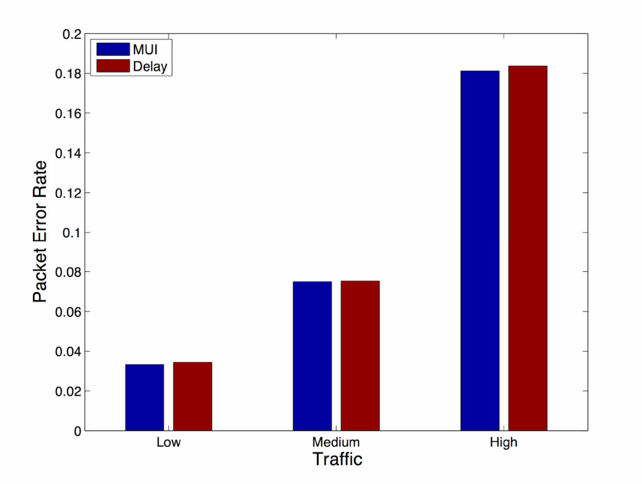

Fig. 2. Packet Error Rate for the coefficient sets defined in Table II.

The improvement on PER is however compensated by the increase in the average number of hops per connection introduced by Set 2, as shown in Fig. 3.

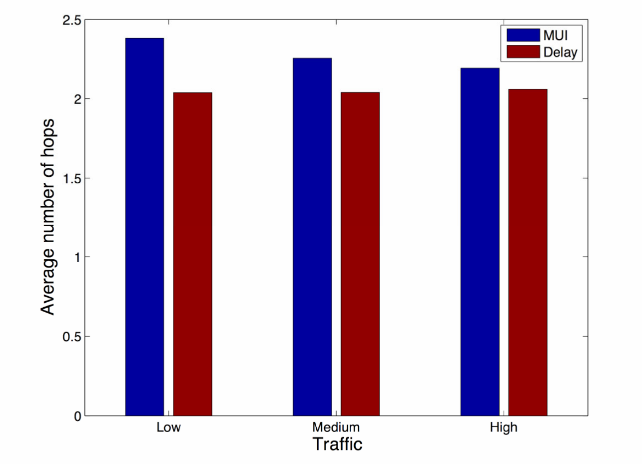

Fig. 3. Average number of hops for the coefficient sets defined in Table II.

Overall, the combination of the lower PER and the higher average number of hops leads to a slightly higher end-to-end packet loss, and thus a lower throughput.

Network lifetime measured for the two coefficient sets is presented in Fig. 4.

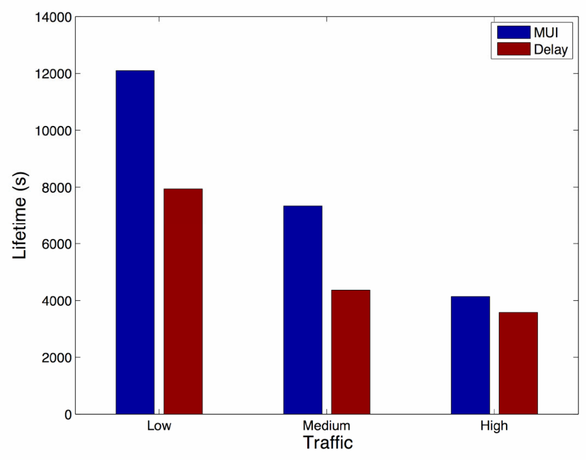

Fig. 4. Network lifetime for the coefficient sets defined in Table II.

Fig. 4 highlights that the adoption of a MUI-aware coefficient set leads to a longer network lifetime, thanks to a

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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 obtained in [2], [16].

V. DISCUSSION AND CONCLUSIONS

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 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.

In the present work 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 in the case of an UWB network scenario 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. End-to-end throughput, on the other hand, does not show significant improvements: this result is justified by the fact that IR-UWB has an intrinsic robustness to MUI. Results suggest thus that the best choice is to select a coefficient set that combines delay and MUI minimization, adjusting the relative weight of the two components according to the specific characteristics of the underlying physical layer in terms of MUI. The adjustment of the cost coefficients should be part of the routing module operations in accordance to the concept of cognitive routing. A possible way to select the weights could be to estimate the PER, in order to determine the impact of MUI in packet loss, thus learning from previous routing decisions and modifying the routing strategy accordingly.

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