Cognitive Radio and Networking for Cooperative Coexistence of Heterogeneous Wireless Networks

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***Abstract*—COST Action IC0902, ”Cognitive Radio and Networking for Cooperative Coexistence of Heterogeneous Wireless Networks”, was launched in December 2009 and coordinates and integrates the research activities on cognitive radio and networks of more than 60 institutions and research projects throughout Europe and worldwide, involving more than 200 researchers. IC0902 aims at becoming the reference point in Europe for research on cognitive radio, leading to the creation of a European platform for cognitive radio and networks by addressing all major technical challenges related to cognitive radio networks design and deployment.**

One of the major research topics addressed in IC0902 is the operation of cognitive devices in the TV White Spaces. In this work recent results obtained in the framework of IC0902 on the design and deployment of positioning systems in the TV White Spaces are presented. A comparison between traditional Wi-Fi-based positioning systems working in the ISM band and TVWS positioning systems is carried out by means of computer simulations, and results show that the favourable propagation conditions characterizing the TVWS frequencies may lead to better positioning accuracy with the additional benefit of lower transmit power levels.

I. Introduction

Contemporary wireless system design must typically incorporate increased bandwidth requirements due to the persistent trend for higher wireless multimedia data rates. Increased bandwidth can be achieved by developing efficient strategies for spectrum management, that include spectrum sharing, coexistence, and cooperation among different wireless networks. This approach has been widely recognized by standardization and regulation bodies in Europe as well as worldwide: the International Telecommunications Union (ITU) has indicated that a flexible approach to spectrum sharing, ranging from liberalization to spectrum trading among different systems and operators, will be a priority issue for the deployment of future wireless systems [1], and in a parallel effort towards increased efficiency in spectrum usage, the IEEE Dynamic Spectrum Access Networks Standards Committee is currently focusing on the development of new standards, able to provide improved flexibility in access mechanisms [2]. Within this context, the cognitive radio concept provides a potential solution for the coexistence of unlicensed secondary with primary licensed systems [3].

Efficiency in spectrum access and efficient resource allocation management has recently been pushed beyond its traditional limits by introducing spectrum sharing and coexistence. This goal has been achieved by typically adopting one of the following strategies:

- Flexible use of the spectrum among different primary systems;
- Cooperative spectrum sharing among primary and secondary licensed systems;
- Spectrum sharing and coexistence among primary licensed systems and unlicensed systems, based on a cognitive radio approach.

Important technical challenges still need to be overcome, however, in order to achieve successful coexistence and cooperation among heterogeneous systems. Open research issues cover a wide range of system aspects, from the hardware component to the physical up to network layer design. In order to address these issues, experts in various aspects of radio design must come together for a joint effort towards system design optimization. Specific aspects that strongly need to be addressed for a successful development in cognitive radio and networks are:

- Design of hardware for reliable spectrum sensing: this is fundamental to unlicensed secondary systems operation [4];
- Definition of algorithms for efficient, dynamic link adaptation [5];
- Design of protocols for cooperation in spectrum sensing and spectrum sharing [6];
- Definition of network functions, such as routing and admission control, that incorporate internal and external network status [7];
- Definition of communication and representation languages for cognitive information exchange [8].

Significant research efforts that focus on flexibility in spectrum management are currently underway in Europe and worldwide, and resources for research on specific aspects of cognitive communication systems are in most cases already in place. Coordination between research teams and organizations is, however, still lacking, leading to potential duplication of work, and overall inefficient use of research funding.

In this context, the COST program [9] offered the perfect framework for the creation of an initiative for coordinating and harmonizing research activities on cognitive communication

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systems, by defining a global vision for cognitive radio and networking, and by allowing stronger interaction and integration between partners and projects working on specific aspects of cognitive radio and flexible spectrum access.
As a result, COST Action IC0902, "Cognitive Radio and Networking for Cooperative Coexistence of Heterogeneous Wireless Networks" [10] was launched in December 2009: the Action aims at integrating the cognitive concept across all layers of the system architecture by creating a joint effort of telecommunications, computer sciences, and electronics communities. Researchers in these fields have little chance to get together and merge efforts towards creative thinking in traditional meetings, such as conferences, since these are rarely interdisciplinary. The IC0902 COST Action aims at becoming the reference point for interaction and cooperation between research groups working on cognitive radio and networks. Projects and partners participating in Action IC0902 have the chance to interact with experts working on similar topics and related aspects of cognitive systems, with direct benefits on research quality as well as scientific and industrial advances. As an added value, graduate students and young researchers have direct access to up-to-date research results, and the possibility to interact with experienced researchers from all over the world, with an obvious beneficial effect on their scientific skills and professional experience.
This work provides an overview of the scope, aims and organization of COST Action IC0902, illustrating the technical objectives of the Action and how they are pursued. The paper also presents recent results related to one of the topics being investigated within the Action, that is the re-use of TV frequencies (the so-called TV White Spaces [11]) by cognitive secondary systems; rather than focusing on the relatively well-known topic of enabling cognitive communications at such frequencies, the paper extends the analysis to a widely unexplored aspect, that is the use of such frequencies for wireless positioning. The paper introduces the problem and presents results to illustrate the potential advantages of deploying wireless positioning solutions in the TV White Spaces.
The paper is organized as follows. Section II introduces the COST Action IC0902, highlighting its scientific objectives, the technical challenges it faces and how it is organized to address them. Section III presents recent scientific achievements on the use of TV White Spaces for positioning, while Section IV draws conclusions.

II. The IC0902 COST Action

Efficient coordination and cooperation of active research projects in Europe is of paramount importance to guarantee alignment of European research centers and companies with worldwide advances in the field. COST Action IC0902 meets this need by providing: 1) coordination across different projects, 2) a framework for the integration of the cognitive paradigm at all layers of the communication architecture, 3) a technology platform to identify complementary skills from various projects and to create synergies to leverage heterogeneity. The cross-layer cognitive paradigm allows in fact the design of a device-wide cognitive platform, and associated language semantics, thanks to the merge of a wide range of expertise, from hardware to applications, provided by over 60 academic and industrial partners involved in most of the relevant EU projects.
The main objective of the Action is to allow for coordinated research and development activities in the field of flexible spectrum use, spectrum sharing, and intersystem coexistence, based on cognitive radio and cognitive networks. The Action enables a vision where networks of communication devices that operate according to scalable cognitive capabilities, interact in order to maximize efficiency in resource utilization. The Action investigates all aspects relevant to the embodiment of the above vision, by adopting a cross-layer design approach, aiming at the definition of cognitive mechanisms encompassing all layers of the protocol stack, from physical to application layers. This approach opens up new possibilities for the definition and implementation of cognitive algorithms and protocols. Reaching above the network layer, up to the application layer, allows to benefit from the multiplicity of physical interfaces, as well as incorporating application requirements in the selection of an optimal wireless interface and configuration.
The cross-layer approach provides a new perspective in the design of cognitive systems, as it introduces a global optimization process that integrates and completes existing cognitive radio achievements in single projects. The final result will be the definition of a European platform for cognitive radio and networks: to reach this goal algorithms and protocols for all layers of the protocol stack will be defined, and a set of standard interfaces as well as a common reference language for interaction between network nodes will be provided. The Action aims at enabling the design of cognitive devices and networks by coordinating research activities capable of addressing five key Technical Challenges (TCs). Four of such technical challenges are related to open scientific and technical issues at specific layers/aspects in the design of cognitive wireless devices, namely: physical layer, MAC, network, and inter-network coordination algorithms and protocols. Based on a bottom-up approach research activities focusing on the above TCs will provide the building blocks for the design of an optimized cognitive engine based on a cross-layer optimization strategy approach in order to be able to receive inputs from and provide outputs to entities working at each layer in the device. The implementation of such a cognitive engine is the fifth TC of the Action. Detailed descriptions of these five TCs can be given as follows.

- TC1 - Definition of cognitive algorithms for adaptation and configuration of a single link according to the status of external environment. Research topics relevant to this TC are: spectrum sensing, adaptive modulation and coding based on spectrum sensing and physical layer design for a single link based on upper layer received inputs. Spectrum sensing, in particular, must include design of effective hardware and efficient algorithms, ranging from simple energy detection to advanced feature extraction for identifying emissions from a variety of wireless systems.

- TC2 - Definition of cooperation-based cognitive algorithms, that take advantage of information exchange at a local level. Operational requirements imposed on cognitive radios may occasionally exceed the capabilities of a single device; in such cases cooperation at a local level among neighbouring devices can lead to significant performance enhancements. Topics relevant to TC2 include, among others, cooperative spectrum sensing algorithms, where groups of cognitive devices exchange information in order to increase reliability and accuracy in spectrum sensing, and cooperative relaying schemes, in order to efficiently address limitations in coverage and network connectivity due to emission limits imposed on secondary cognitive radio devices;
- TC3 - Definition of network-wide mechanisms for enabling the cognitive approach. Research issues relevant to TC3 encompass all network-wide functions required for the deployment of cognitive networks of smart secondary devices that cooperate in order to coexist with primary systems, such as admission control strategies capable of introducing cognitive aspects in the decision on whether to admit new devices in the network while maintaining the network in a condition of stability, and routing protocols capable of selecting end-to-end paths based on observations that are carried out at lower layers;
- TC4 - Definition of mechanisms for intersystem coexistence and cooperation. Although spectrum sensing will play a key role in ensuring coexistence between cognitive devices and legacy radio systems, the definition of intersystem communication and coexistence mechanisms will enable efficiency in flexible spectrum sharing between secondary devices and primary systems. Particular attention will be devoted to the definition of explicit communication mechanisms, such as cognitive pilot channels (CPC). The definition of such mechanisms encompasses both scientific aspects, such as information representation languages, and standardization aspects, that are fundamental in order to guarantee a widespread adoption of the proposed communication mechanisms.
- TC5 - Definition of a cross-layer cognitive engine. The design of a cross-layer cognitive engine will be carried out by allowing the engine to receive inputs from entities running at all layers of the device. The cognitive engine will also provide inputs to the same entities based on the decisions it has taken. The design of a cross-layer cognitive engine will include the capability of taking advantage of multiple network interfaces that are often available in modern radio terminals, as well as the possibility of combining heterogeneous information in selecting the best strategy. Definition of an efficient representation language for the exchange of information and of advanced artificial intelligence algorithms, capable of determining the optimal strategy for all aspects of the device operations, are also part of this TC.

Research activities in IC0902 are organized in Working Groups (WG) that map 1 to 1 the Technical Challenges defined above:

- WG1 focuses on the research issues related to TC1, and will thus address all aspects related to single link adaptation, such as spectrum sensing, measurement and shaping, and interference suppression.
- WG2 focuses on the definition of cognitive mechanisms taking advantage of cooperation of devices in spatial proximity, according to the research issues identified as part of TC2.
- WG3 deals with all research aspects relevant to TC3, with particular focus on the extension of cognition from the single network device to the whole network.
- WG4 addresses intersystem cooperation and coexistence under both technical and standardization/regulation points of view. From a scientific point of view, WG4 addresses the research issues relevant to the challenge TC4 previously described. Furthermore, given the strong importance of regulation and standardization in the activities carried out in TC4, this Working Group also acts as a gathering point for the organization and coordination of contributions to regulation and standardization bodies from partners of the Action.
- WG5 focuses on the introduction of cognition in devices above the network layer, exploring the definition of a cross-layer cognitive engine. The Working Group will take advantage of the results obtained in the other Working Groups in order to identify the main capabilities required for the cross-layer engine to enable an effective use of available information and device characteristics, such as the presence of multiple wireless interfaces, when available, while taking into account application requirements.

IC0902 also addresses a few vertical research topics that encompass all TCs. An excellent example of such a topic is the definition of information representation languages as well as the introduction of learning and artificial intelligence methods in the design of the components forming the cognitive engine. These vertical research topics are addressed by Special Interest Groups (SIGs), which were defined and created in addition to the Working Groups as a dynamic transversal texture of the Action. SIGs gather experts from different WGs on common research issues. Four SIGs are presently active within the Action:

1) Information representation languages - the SIG involves experts of traditionally distant fields (radio, computer science, artificial intelligence). This topic is instrumental for both intra-device cognitive entities, and intra and inter-network cognitive protocols. This SIG investigates innovative solutions in the definition of representation languages by taking advantage of synergies between experts working on different topics in different WGs.
2) Learning and artificial intelligence - the SIG allows experts to work together and possibly generate new

knowledge towards the application of machine learning and artificial intelligence to the conception of the cognitive platform.

3) Mobility management for cognitive wireless networks - the SIG focuses on the conception of models that are adequate to specific network typologies, and analyzes techniques related to the topology control in cognitive mobile radio networks.
4) Positioning in cognitive networks - the SIG focuses on the potential impact of position information and positioning techniques in the definition and deployment of cognitive radio networks.

III. Positioning in TV White Spaces

This Section presents and discusses results obtained in the framework of COST Action IC0902 on the topic of TV White Spaces, focusing on their use for Wi-Fi based positioning systems.

A. White Spaces definition

The term *TV White Spaces* is referring to the frequencies licensed for a broadcasting service but not used on designated geographical area. Many initiatives emerged recently to reallocate those parts of the spectrum as unlicensed and make them accessible to unlicensed devices under the guaranty that they will not interfere with existing or future broadcasting services. The size of white spaces depends of geographic areas. As evidenced in [12], TV White Spaces (TVWS) arise for three reasons:

1) The need for guard spaces between analog TV services in the same license area. Because of the superior performance characteristics of digital terrestrial television technologies, the need for guard intervals between DTV services in the same license area can be significantly reduced or eliminated.
2) The need for geographic separation between TV services that are in different license areas but are broadcasting on the same channel.
3) The non-allocation of some channels in areas where there is either a limited supply of broadcasting services or limited demand of broadcasting services (typically because of the increasing range of technologies that can be used to deliver broadcasting services).

Still in [12] the authors state that a device, which opportunistically uses these available frequency spaces, is commonly referred to as a *white-space device* (WSD). The TVWS usage by WSDs requires an adequate protection of primary/incumbent users; regulation activities are presently ongoing in US (carried out by the FCC [11]), UK (by Ofcom [13]) and Europe ([14]), although at different stages of completion.

B. White Spaces: the new WiFi?

Applications that could benefit from white spaces operation definitely include Wi-Fi at TV frequencies. It could be useful for:

1) Rural broadband access for subscribers in densely forested areas. If there is a line of sight, Wi-Fi at 5 GHz is more useful (and has more capacity and low cost) but when subscribers are hidden by trees, TV frequencies are less scattered.
2) Wireless LANs inside heavy masonry buildings or those with plaster on metal wire lath.

In 2008 Google and Microsoft announced their interest in using TVWS for an enhanced type of Wi-Fi like Internet access, called Wi-Fi 2.0, Wi-Fi on steroids, or White-Fi. Although Wi-Fi over WS is still in its infancy, its resemblance to today's Wi-Fi hotspots suggests that it may become a "killer application" in CR-based wireless networks. By utilizing more favorable spectrum bands than the ISM, the new Wi-Fi will be able to support QoS guarantees and resource-intensive multimedia services more easily than the current Wi-Fi. The advantages could however extend to other Wi-Fi based applications, beyond communications. The rapid growth of the number of wireless access points in urban areas has in fact brought forth the WiFi based positioning system (WPS) that can solve the positioning in certain situations (like indoors). Some providers like *Skyhook Wireless*, *Google* or *Fraunhofer Institute* maintains a public database that can be accessed through an API, and get the position based on the access points are accessible from a terminal (the AP location is associated with the MAC addess of that AP). Unfortunately, despite the high density of access points available for WPS, the coverage provided by such WiFi networks is currently rather patchy. This is due to a combination of the relatively stringent regulatory caps on transmit power levels of WiFi in Europe, e.g., 20 dBm (100 mW) in the 2.4 GHz band and also due to the high wall and floor penetration loss suffered by signals in the ISM bands. By switching operation of the network from the ISM bands to TVWS spectrum, the above coverage limitations could be overcome, leading to a significant improvement in positioning accuracy.

C. Impact of propagation and channel characteristics on positioning error

In [15] a model for uncertainty of an RSS based localization system inspired by [16] and [17] is proposed. Typically, in RSS approach, a signal strength vector $s(x, y) \in \mathcal{S}$, consisting of the received signal strengths from n different Access Points is associated with each location $(x, y) \in \mathcal{A}$, where $\mathcal{A}$ is the considered area. Using propagation models a mapping relationship $\mathcal{M} : \mathcal{A} \longrightarrow \mathcal{S}$ is generated: the location of the target is estimated by obtaining the signal strength vector at the target device and finding the closest matching vector from $\mathcal{M}$. Thanks to this mapping relationship one can relate the uncertainty of the signal strength domain to the error in the positioning plane, by using the concept of Circular Error Probability (**CEP**). CEP is defined as the radius of a circle, centered about the mean, whose boundary is expected to include 50% of observation. Considering an unbiased estimation, the center of this circle is the real position of the target: so the CEP is an approximation for the positioning mean error. In [15] the network and channel parameters that influence the value of the CEP, and thus of the positioning error, were investigated, highlighting a strong dependence of the CEP on the average distance between APs, the number of APs, and the channel propagation constant γ.

Results in [15] show that for a given number of landmarks, the value of CEP increases by increasing the distance between APs and that, coherently, if one considers more APs for a fixed area the CEP decreases.

Finally, the analysis in [15] showed that the accuracy increases with increasing γ, despite the signals from the APs becoming weaker. This somewhat counter-intuitive result can be explained by the fact that as γ increases, the signal level is more sensitive to location changes. That is: a large γ is given by a large propagation constant and this implies rapid change in signal strength over distance and hence a given variation in signal strength will correspond to a smaller distance than with a smaller propagation constant. Overall, however, the model shows that by increasing the number of APs one achieves better performance also when γ is much smaller.

D. TVWS versus Wi-Fi: positioning systems

The net effect of switching Wi-Fi operations to TVWS frequencies from an end user point of view is an increase in transmission range. In turn, a device trying to establish its position by WPS can reach a greater number of access points. As discussed in the previous subsection, the positioning error depends, beyond various parameters, on the available number of access points. In particular positioning error decreases when the number of APs increases. This idea is depicted in Fig. 1, where range and number of APs are shown for a device operating at $2.4GHz$, $790MHz$ and $490MHz$ (the outers of TV bands), adopting the widely used **Log-distance path loss model**, characterized by the following equation:

$$P_{LdB} = -27.55 + 20 \log f_{MHz} + 10\gamma \log d + X_g \quad (1)$$

where:

- f_{MHz} is the carrier frequency expressed in MHz;
- γ is the path loss exponent, usually taken between 2 (= free space loss exponent) and 5 (dense urban);
- X_g is a random variable $\sim \mathcal{N}(0, \sigma^2)$ to take into account fading, cable and body losses.

It is evident that the range and the APs number obtained by the terminal operating in TV bands is much larger than that which works in the ISM one. Moving from the analytical model introduced in the previous subsection, a set of simulations was devised to carry out an extensive performance analysis for a positioning system working in the TVWS compared to traditional Wi-Fi operation.

In the simulations a certain number of access points (N_{ap}) were distributed in a squared area, of area A, according to a random uniform distribution. For the Wi-Fi case a classic $802.11/b$ system with $20MHz$ channel bandwidth and data rate $11Mb/s$ was considered, while for the TVWS, since

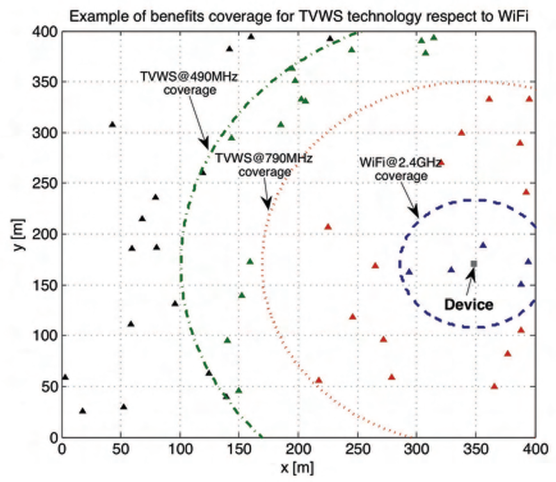

Fig. 1. Transmission range and reached APs for WiFi and TVWS ($P_{tx} = 30dBm$, Log-distance path loss model)

TABLE I
PROPAGATION MODEL AND NETWORK SETUP PARAMETERS

Parameters	Value
γ	3.2 (WiFi) - 3 (TVWS)
σ^2	6 dB
N_{ap}	30
$A(area)$	300 m^2

a standard system does not exist as of today, a *possible* $802.11/af$ system based on $802.11/n$ was assumed. Only one available TV channel was assumed, so the channel bandwidth is $8MHz$; by considering for example a $16QAM$ modulation scheme and a convolutional code with code rate of $\frac{1}{2}$ one obtains approximately a data rate of $11Mb/s$. Receiver characteristics were derived from those of CISCO Aironet 350 access points, with a receiver sensitivity (for $f_b = 11Mb/s$) of $-82dBm$. All the parameters used in the simulation are summarized in Table I and II.

Matlab simulations results are shown in Fig. 2 and 3. From Fig. 2 it is evident that, for the same transmitted power, the average number of APs reached by a TVWS device (both 470 and 790 MHz) is much greater than the WiFi one. The WiFi device is in fact able to cover only a little more than 5 APs

TABLE II
SETTINGS USED FOR COMPARING DEVICES OPERATING IN THE CONSIDERED SPECTRAL BANDS

Parameters	WiFi	TVWS
Radio frequency	2.4 GHz	470,790 MHz
EIRP	$14.77 \div 20dBm$	$14.77 \div 20dBm$
Channel Bandwidth	20 MHz	8 MHz
Receiver sensitivity	-82 dBm	-82 dBm

for its maximum transmitted power value when the TVWS one always reaches more than half of the total APs.

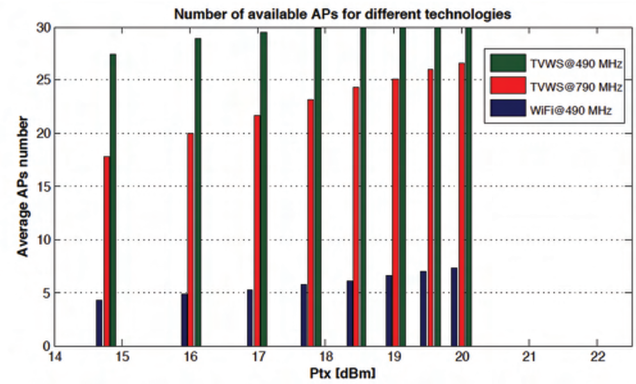

Fig. 2. Number of reached APs for different spectral bands

This is reflected in localization performance, as shown in Fig 3. The TVWS device largely outperforms the Wi-Fi one, by obtaining a very small average error value even with the minimum transmitted power value considered: for $14.77dBm$ the average positioning error obtained by a TVWS-system is more than 6 meters lower compared to a traditional Wi-Fi-based positioning system.

IV. Conclusion

In this work the scope, objectives and organization of the COST Action IC0902 were introduced. COST Action IC0902 aims at becoming the reference point for European research on Cognitive Radio networks, thanks to the involvement of more than 60 institutions and research projects both in Europe and worldwide, and to the coordination and integration of the research efforts of Action partners.

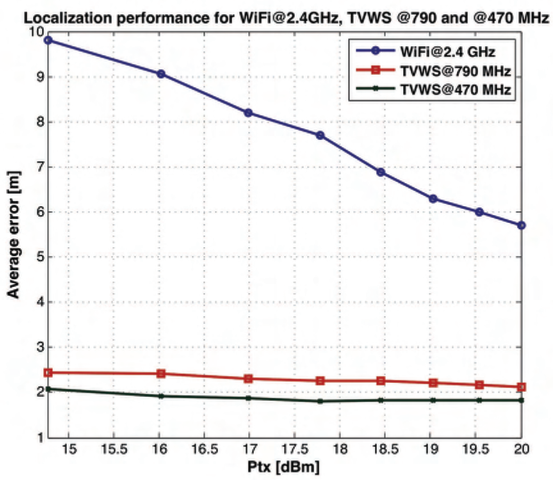

Fig. 3. Average localization error vs transmitted power

Next, the paper presented some of the results obtained in the framework of Action IC0902 on the topic of wireless positioning in the TVWS bands, highlighting the potential advantages achievable by adopting a cognitive radio technology capable of taking advantage of unused frequency channels in the TV bands, thanks to the favourable propagation conditions. Results also suggest that positioning systems working in the TVWS can offer the same performance of the existing ones operating in the ISM bands by using less energy, a very attractive feature in modern communication systems, aiming at a *green* behavior.

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