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SYSTEM CAPACITY LIMITS INTRODUCED BY DATA FUSION ON COOPERATIVE SPECTRUM SENSING UNDER CORRELATED ENVIRONMENTS*

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Abstract: *Spectrum sensing, the cornerstone of the Cognitive Radio paradigm, has been the focus of intensive research, from which the main conclusion was that its performance can be greatly enhanced through the use of cooperative sensing schemes. Nevertheless, if a proper design of the cooperative scheme is not followed, then the use of cooperative schemes will introduce some limitations in the network perceived capacity. In this paper, we analyze the performance of a cooperative spectrum sensing scheme based on Data Fusion, by measuring the perceived capacity limits introduced by the use of Data Fusion on cooperative sensing schemes. The analysis is supported by evaluation metrics which accounts for the perceived capacity limits. The analysis is performed along the data fusion chain, comparing several scenarios encompassing different degrees of environment correlation between the cluster nodes, number of cluster nodes, and sensed channel occupation statistics. Through this study, we motivate that to maximize the perceived capacity by the cooperative spectrum sensing, the use of data fusion needs to be performed in a fractioned way, i.e., that the fusion must be done between subsets of the nodes in a cluster.*

Keywords: *cooperative spectrum sensing, capacity limits.*

1. Introduction

The cornerstone of a Cognitive Radio ad-hoc network [1] is its ability to adapt to the surrounding environment, which can only occur if accurate information of the surrounding environment is made available. This

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environment awareness is accomplished by the Spectrum Sensing, which has been covered extensively in literature [2, 3], and falls into what is known as detection theory, presented in detail in [4]. Spectrum sensing is realized as a physical and Medium Access Control (MAC) layer mechanism [5]. The physical layer sensing focuses on detecting signals, and the detection methods put in place can be classified as, either coherent (e.g., Matched Filter Detection [2]), non-coherent (e.g., Energy Detector [6]) or Feature Detection (Cyclostationary Detection [2]). The MAC layer part of the spectrum sensing focuses on when to sense and which spectrum to sense.

The channel conditions, which depend on the path loss, multipath, shadowing and local interference, affect the sensing requirements. The combination of these phenomena can result in regimes where the signal *SNR* is below the detection threshold of the sensor, and therefore the detector will not be able to detect the signal transmitted by the transmitter. Now consider the example depicted in **Figure 1**, where there is a primary system and cognitive radio system, both composed by a transmitter and receiver. The cognitive radio transmitter is not able to detect the transmission of the primary transmitter, because it is outside the primary transmission range, i.e., the *SNR* is below the cognitive radio transmitter detection threshold. So the cognitive radio transmitter sees the channel as vacant and therefore decides to transmit on it, causing interference to the primary receiver. This is known as the hidden node problem. So even if a transmission is not detected by the sensing node, it does not mean that there is not one there, namely because the sensing node may be under a deep fade, due to an obstacle in the terrain.

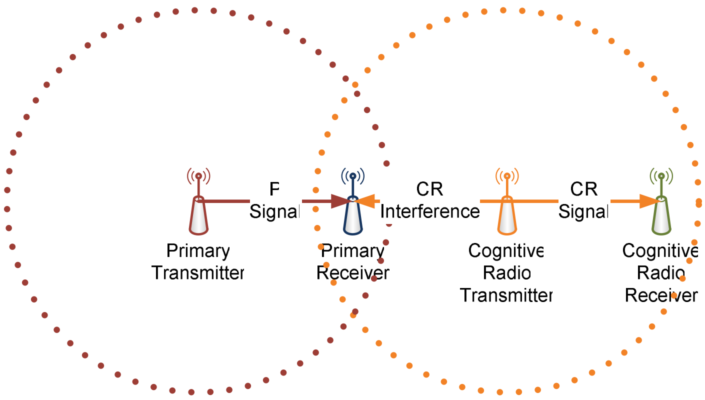

Figure 1. *Hidden node problem*

To overcome this limitation, in [7-10] it was proposed the use of cooperation in the spectrum sensing. Since the signal strength varies with the sensor location, the worst fading conditions can be avoided if multiple sensors in different spatial locations share their sensing measurements, i.e., take advantage of the spatial diversity. Most of these proposed cooperative methods are based on data fusion techniques to perform the decision on what is the actual state of the spectrum. In [11] we did a comprehensive study on the effect of correlation on cooperative spectrum sensing, besides providing a theoretical framework based on Bayesian inference, the paper's main conclusion was that under certain correlation conditions the use of cooperation may not be worthwhile.

Now consider the example depicted in **Figure 2**, where there is a primary system and cognitive radio system, both composed by a transmitter and receiver. Both the cognitive radio and primary transmitters are able to detect each other, but the receivers are outside the interference zone, i.e., the cognitive radio receiver is outside the range of the primary transmitter, and the primary receiver outside the range of the cognitive radio transmitter, so if both transmitters would do a transmission there would be no interference, but since the transmitters detect each other then only one of them transmits at a given time. This is known as the exposed node problem.

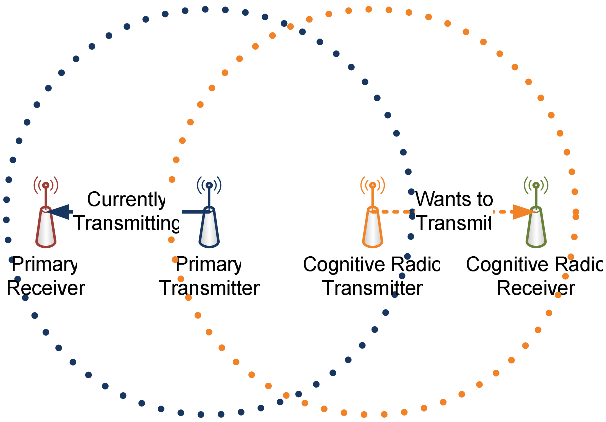

Figure 2. *Exposed node problem*

In this paper, we want to motivate that data fusion should be done with care, so to ensure that by trying to limit the effect of the hidden terminal problem, we are not increasing the effect of the exposed node problem, illustrated in **Figure 2**. The effect of the exposed node problem is increased by fusing together sensing results taken from spatial positions apart, and therefore by combining sensing results from positions far apart, one is losing the information about possible available spectrum opportunities, i.e., losing information about the spatial diversity. This phenomenon is illustrated in **Figure 3**, where the colored regions represent where the spectrum is available, and non-colored where the spectrum is occupied. After the Data Fusion occurs the information about the regions where the spectrum was available disappear, therefore causing the system to lose that information.

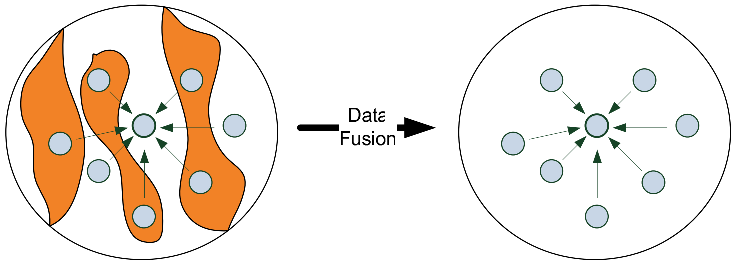

Figure 3. *The drawback of using data fusion, the loss of spatial diversity*

In [12, 13] a cluster based cooperative spectrum sensing scheme for an ad-hoc based scenario was proposed. The proposed scheme allows assigning to the nodes of each cluster a specific channel to sense. This assignment is done based on the estimated channel occupation statistics. The proposed scheme implementation can be done in both a centralized [12] and decentralized [13] fashion. In the centralized implementation, the elected cluster head is responsible for collecting and fusing the local decisions of each of the cluster nodes, with the purpose of estimating the monitored channels occupancy. The estimated channel occupations statistics are then used by the cluster head to assign each node in the cluster a channel to sense. In the decentralized implementation, each of the cluster nodes gathers and fuses the local decisions of the other cluster nodes and from there it estimates the monitored channels occupancy. Using the estimated information the cluster node then decides which channel to sense in the next sensing session.

In this paper, an extension of the work presented in [14], we study the capacity perceived by the scheme proposed in [15], focusing on the loss of perceived capacity introduced by the use of data fusion. This analysis is done along the data fusion chain, comparing several scenarios encompassing different degree of environmental correlation between the cluster nodes, number of cluster nodes and sensed channel occupation statistics.

The remainder of this paper is organized as follows. In **Section 2**, we give the problem definition, methodology, system design and capacity evaluation metrics. In **Section 3**, the capacity limits according to the defined metrics are presented. Finally, **Section 4** concludes the paper with a recap of the contribution and of the main obtained results, as well as an outlook on further studies.

2. Problem Definition and Methodology

2.1 Problem definition and methodology

The problem we tackle in this paper is the following: “*How does the use of data fusion in the cooperative spectrum sensing mechanism affect the system perceived capacity?*”

The methodology followed to answer this question mirrors the article structure, and is the following: first we introduce the system capacity evaluation metrics, then we give a brief review of the system design and scenario assumptions, and thereafter we compare the system's perceived capacity along the data fusion chain while focusing on the factors that influence it, like the channel occupation and environment correlation between the sensing nodes. The study is then concluded with the highlights from the analysis and also with the possible future directions which might increase the system's perceived capacity.

2.2 System design overview

Here we give an overview of the system design presented in [12, 13, 15], and explain where in the system we focus our analysis.

Consider a cooperative spectrum sensing mechanism for an ad-hoc Cognitive Radio network, composed of network nodes, organized in clusters, and capable of operating on and sensing any narrow band channel of a targeted range of spectrum. Each cluster node is assumed to have available two logical types of channel, which we depict in **Figure 4**. The Control Channel (CCH) where all control information is exchanged and the access method is CSMA/CA, and the Data Channel (DCH) through which the users data are exchanged and of which the access method is out of scope.

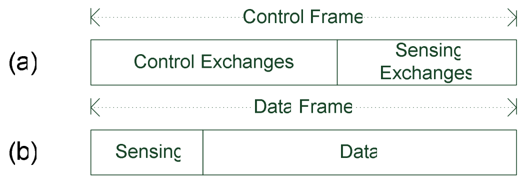

Figure 4. *a) Control Frame, b) Data Frame*

We consider that each sensing node performs the sensing through the use of an Energy Detector (ED) [6, 7], a non-coherent sensing scheme. The distributed spectrum sensing mechanism, depicted in **Figure 5**, is to ensure that all of the sensing nodes in the cluster have updated and synchronized information about the state of the targeted spectrum. In [12, 13] this mechanism was used as the backbone for the centralized and decentralized mechanism implementation, which has in common all the steps except for the "Choose Spectrum to Sense Next" step.

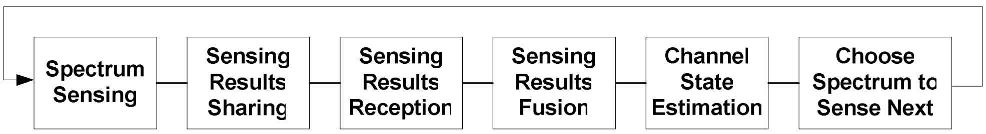

Figure 5. *Distributed spectrum sensing mechanism flow [12, 13, 15]*

The distributed spectrum sensing mechanism flow steps, depicted in **Figure 5**, are:

- **Spectrum Sensing –** each cluster node performs the sensing through the use of an Energy Detector, therefore at the end of the spectrum sensing a binary decision regarding the status of the sensed channel is taken by each node, i.e., if either the channel is occupied or free. The spectrum sensing occurs in the DCH in the “Sensing” period, depicted in **Figure 4b**;
- **Sensing Results Sharing –** each cluster node shares the result of the binary decision reached in the spectrum sensing. The sharing is done by broadcasting through the CCH during the “Sensing Exchanges” period, depicted in **Figure 4a**;
- **Sensing Results Reception –** each cluster node receives the results broadcasted by the remaining cluster nodes through the CCH;
- **Sensing Results Fusion –** at this point, the receiving nodes fuse together the sensing results received from the other cluster nodes. Note that the fusion process is done separately for each sensed channel. The data fusion scheme used is classified as a synchronous hard decision, meaning that the result is a binary decision;
- **Channel State Estimation –** the estimation of the channels state is done based on past observations and current observations, when available, i.e., if the channel in question was sensed. Through this process it is possible to obtain updated statistics of the network targeted channels;
- **Choose Spectrum to Sense Next –** this step depends on the approach chosen to implement the mechanism, i.e., if the mechanism is centralized or decentralized coordination. In the centralized approach one of the cluster nodes decides which channel should be sensed by each of the cluster nodes, while in the decentralized approach, the decision on which channel to sense is done independently by each of the cluster nodes. Both approaches perform this choice according to the channels occupation statistics.

In this paper, we focus on the “Sensing Results Fusion” step, where, the cluster nodes fuse together the sensing results, received from the other cluster nodes, separately for each sensed channel, as illustrated in **Figure 6**.

The data fusion scheme considered is of the synchronous hard decision type, which uses predefined fusion rules to achieve the data fusion. The data fusion rules considered are of the counting rule type, i.e., they count the number of sensors detecting a given state and then compare it with a decision threshold to reach a decision about the state of the channel. This decision threshold affects both the global probability of false alarm as well as the global probability of detection.

A fusion rule is a logical function with N binary inputs and one binary output; therefore there are 2^{2^N} possible fusion rules, when there are N binary inputs to the fusion centre. Here we consider a subset of those rules, which are classified as counting rules, i.e., the output of the logical fusion is only positive when there are at least n positives in the binary input. In **Table 1** there are shown the global expressions for the probability of detection and false alarm when all the sensors are under independent conditions.

Table 1.
Counting rules performance

Fusion Rule	**Type**	**Global P_d**	**Global P_fa**
OR	1-out-of-N	$1-(1-P_\mathrm{d})^N$	$1-(1-P_\mathrm{fa})^N$
MAJORITY	$(N+1)/2$-out-of-N	$1-(1-P_\mathrm{d})^{(N+1)/2}$	$1-(1-P_\mathrm{fa})^{(N+1)/2}$
AND	N-out-of-N	P_d^N	P_fa^N
n-ARY	n-out-of-N	$1-(1-P_\mathrm{d})^n$	$1-(1-P_\mathrm{fa})^n$

In [15] an Adaptive counting rule was proposed. This counting rule adapts its counting threshold so to achieve the best performance according to the experienced correlation. The adaptive rule accomplishes this by adapting the decision threshold dynamically, according to the correlation experienced by the underlying sensors, while not having implicit information about the correlation. The correlation information is instead derived from an adaptive feedback mechanism, which uses the information gathered from the channel access, i.e., it checks the actual state of the channel with the estimated state.

2.3 Evaluation metrics

In this subsection, we define what we mean by system's perceived capacity, from a cooperative spectrum sensing mechanism, along the data fusion chain.

Figure 6 depicts the steps that constitute the data fusion chain, where U_e, U_s and U_df represent the perceived state of the sensed channel at each step. U_e represents the node experienced state of the channel targeted for sensing. Through U_s is represented the perceived state of the channel after sensing. Finally, through U_df we represent the perceived channel state after the data fusion. The values that each of these states can take are,

$$U_{\mathrm{e},i}, U_{\mathrm{s},i}, U_\mathrm{df} = \begin{cases} 1, & \text{if channel is free} \\ 0, & \text{if chanel is in use} \end{cases} \quad (1)$$

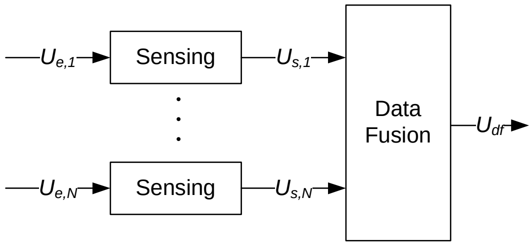

Figure 6. *Data fusion chain*

To illustrate the meaning of system perceived capacity, first consider that in a cooperative spectrum sensing session are participating several sensing nodes, and that each of these experiences different signal strength, due to path loss, fast fading, shadowing, etc. Now if one considers that at the location of each of these sensing nodes, the channel is deemed free for use if the signal strength is below a given *SNR* threshold, then it is expected that due to the mentioned varying channel conditions, some of the nodes will experience the same channel as free while other will experience it as occupied, i.e., when the signal is above the *SNR* threshold. Note that what we mean by experienced channel state refers to the actual state of the sensed channel at a particular geographical location, given by U_{e}, i.e., before the sensing takes place.

Following the data fusion chain in **Figure 6**, we exemplify in **Figure 7** the status of the perceived channel state at each step of the data fusion chain, given by U_{e}, U_{s} and U_{df}. Each of the figure's blocks represents a sensing node and its color the perceived channel state.

When comparing the experienced spectrum state, U_{e}, and sensed spectrum state, U_{s}, it can be seen that some of the nodes fail to detect that the channel is occupied, i.e., a missed detection occurs, while other nodes judge the channel as occupied when it is not, i.e., a false detection or false alarm occurs. Both events have impact on the perceived system capacity, the missed detections because they cause the node to perceive a channel as free when it is occupied, and the false alarm because the node perceives the channel as occupied when it is free. So in the former you assume to have more resources than available, while in the latter you miss the available resources.

After the data fusion, U_{df}, all nodes are assumed to perceive the channel state that resulted from the data fusion. From the example in **Figure 7**, after the data fusion all nodes are assumed to perceive the channel as occupied, although some of the nodes actually perceive the channel as free, causing a decrease of the system perceived capacity.

To measure the system perceived capacity at the different stages of the data fusion chain, we define below several metrics. What we mean by capacity in the context of this work is the number of sensing nodes that are experiencing or perceiving the channel state as free.

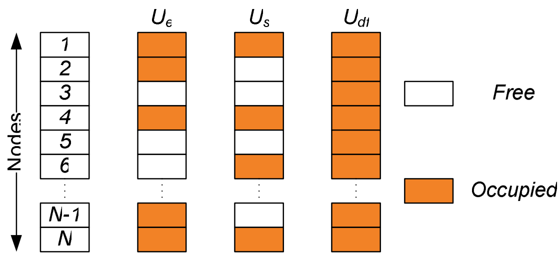

Figure 7. *Spectrum sensing capacity illustration*

The potential capacity of the set of considered sensing nodes, given by C_r, is defined as

$$C_\mathrm{r} = \frac{\sum_{i=1}^{N} U_{\mathrm{e},i}}{N}, \qquad (2)$$

where $U_{\mathrm{e},i}$ is the experience channel state of the i^th sensor node and N the number of nodes. This metric allows measuring the fraction of nodes that are experiencing a free channel, i.e., before the sensing takes place.

The post-sensing capacity of the considered sensing nodes set, given by C_s, is defined as

$$C_\mathrm{s} = \frac{\sum_{i=1}^{N} U_{\mathrm{s},i} U_{\mathrm{e},i}}{N}, \qquad (3)$$

where $U_{\mathrm{s},i}$ is the sensed channel state of the i^th sensor node. This metric allows measuring the fraction of nodes that perceive the sensed channel as free when the channel is in fact free. Therefore when a node perceives the channel as occupied when it is actually free, i.e., a false alarm as occurred, then the C_s does not consider it. So the occurrence of false alarms is the phenomenon that causes the C_s to be lower than the C_r.

The post-data fusion capacity of the set of the considered sensing nodes, given by C_df, is defined as

$$C_\mathrm{df} = \frac{U_\mathrm{df} \sum_{i=1}^{N} U_{\mathrm{e},i}}{N}, \qquad (4)$$

where U_{df} is the decided spectrum state after the data fusion. This metric measures the fraction of nodes of the set that are indeed experiencing a free channel when the perceived state resulting from the data fusion is as free channel. Here the occurrence of false alarms, i.e., perceiving the channel as occupied and it is free, causes the C_{df} to be lower than the C_{r}.

These three metrics give us the system's perceived capacity at three different points of the data fusion chain, and the difference among them accounts for the probability of false alarm, i.e., of perceiving the spectrum as occupied when it is in fact free. But these metrics do not account for the effect of perceiving erroneously the channel state as free, i.e., they do not account for the occurrence of misdetections.

To measure the fraction of nodes which perceive erroneously the channel as free post sensing, we define the post-sensing false capacity, given by FC_{s}, as,

$$FC_{\text{s}} = \frac{\sum_{i=1}^{N} U_{\text{s},i} * \left(1 - U_{\text{e},i}\right)}{N} \qquad \textbf{(5)}$$

where $U_{\text{s},i}$ is the sensed channel state of the i^{th} sensor node. This metric allows measuring the fraction of nodes that perceive the sensed channel as free when the channel is in fact occupied, this achieved by using the term $\left(1 - U_{\text{e},i}\right)$.

To measure the fraction of nodes which perceive erroneously the channel as free post data fusion, we define the post-data fusion false capacity, given by FC_{df}, as

$$FC_{\text{df}} = \frac{U_{\text{df}} \sum_{i=1}^{N} \left(1 - U_{\text{e},i}\right)}{N}, \qquad \textbf{(6)}$$

where U_{df} is the decided spectrum state after the data fusion. This metric measures the fraction of nodes of the set that are indeed experiencing an occupied channel when the perceived state resulting from the data fusion is as free channel.

To visualize better the obtained results, we normalize C_{s} and C_{df} in terms of C_{r}, while the FC_{s} and FC_{df} is normalized in terms of $\left(1 - C_{\text{r}}\right)$.

Through these five metrics it is possible to characterize completely the perceived capacity at each point of the data fusion chain, and therefore to understand and quantify the capacity limits achieved by using different data fusion schemes as well of not performing data fusion.

3. Capacity Limits Assessment

3.1 Effect of environment correlation on system capacity

Here we analyze the effect of varying correlation between the sensing nodes on the capacity perceived by the cooperative spectrum sensing scheme. The simulation setup is shown in **Table 2**.

Table 2.
Simulation parameters

Parameter	Value
Primary Signal Duty Cycle	0.5
Number of Nodes in the Cluster	20
Detector	Energy Detector
Detector's P_d	0.83
Detector's P_{fa}	0.05
SNR Threshold	–7.5 dB
Correlation Index Variation	0 to 1

To understand how the Capacity and False Capacity of a cooperative spectrum sensing mechanism vary with the average correlation index, we plot **Figure 8** and **Figure 9**, respectively. Both figures consider the results obtained when using the adaptive fusion rule, an adaptive fusion rule proposed on [15], and the OR rule.

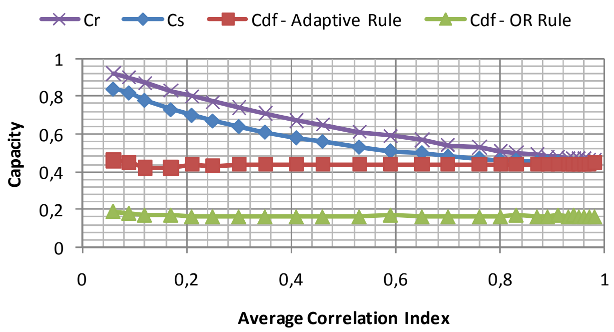

Figure 8. *Capacity vs. Average Correlation Index*

From **Figure 8**, it is seen that the potential capacity of the cooperative spectrum sensing mechanism, C_r, decreases with the increase of the average correlation index. This occurs because the higher is the correlation the lower is the spatial diversity leading to lower potential capacity.

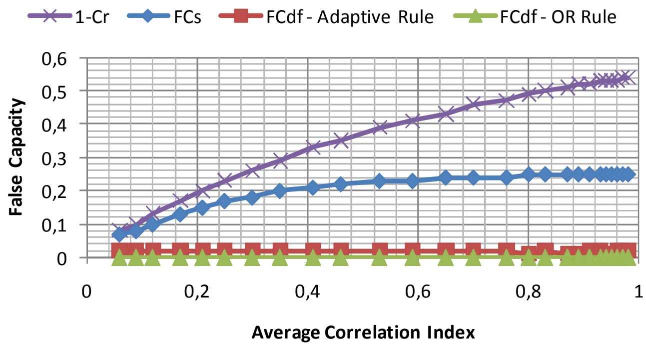

Figure 9. *False Capacity vs. Average Correlation Index*

As expected the C_s follows the same behavior, and the observed gap between the C_r and C_s is related to the probability of false alarm of the individual nodes. It should also be noted that the Data Fusion schemes maintain the same perceived capacity along the average correlation index increase. This occurs because the purpose of Data Fusion is to collate correlated measurements to improve the detection of a phenomenon, which in our case is the presence of a signal in the sensed channel, and therefore the more correlated are the nodes the better is the Data Fusion schemes performance, as observed when normalizing the C_{df} in regard to the C_r, as depicted in **Figure 10**.

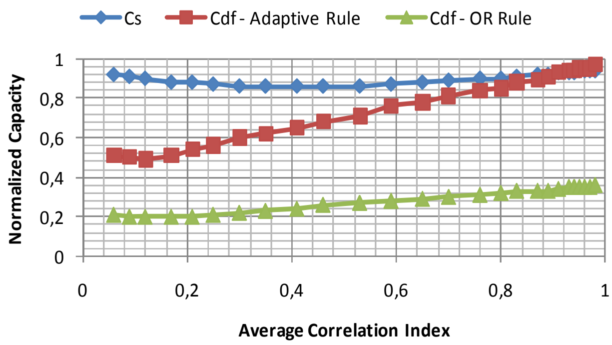

Figure 10. *Normalized Capacity with respect to* C_r

In **Figure 9** it is depicted the False Capacity, and as expected $1-C_r$ increases with the increase of the average correlation index, this behavior is followed by the FC_s, although when the average correlation index is above 0.4, i.e., when there is a high degree of correlation, the FC_s growth rate decreases.

To further illustrate the dependence of the Capacity and False Capacity, in **Figure 10** and **Figure 11** are depicted respectively the normalized Capacity and normalized False Capacity.

From **Figure 10** it can be seen that the normalized C_s remains almost the same independently of the average correlation index, while when considering the case of C_{df}, for both fusion rules, there is an increase on the achieved capacity with the increase of the average correlation index. Also, the Adaptive rule allows for a higher perceived capacity than the OR rule.

The perceived capacity is proportional to the probability of false alarm. Then it can be concluded that the reason why the adaptive rule C_{df} is higher than the C_{df} of the OR rule is because the adaptive rule allows to achieve a lower probability of false alarm. The C_s is higher than the C_{df} of the data fusion schemes, since the individual probability of false alarm is lower than the one achieved when using data fusion schemes.

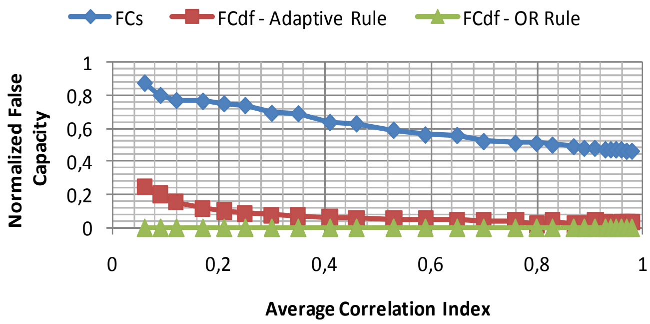

Figure 11. *Normalized False Capacity with respect to* $(1-C_r)$

From **Figure 11** it can be seen that in all cases the Normalized False Capacity (*NFC*) decreases with the increase of the average correlation index. Note that the False Capacity as defined relates to the probability of missed detection. This can be confirmed by observing that the *NFC* for the FC_s is higher than the FC_{df}, since the purpose of using data fusion schemes is to decrease the probability of occurring missed detections.

From **Figure 10** and **Figure 11**, it is observed that although the sensing without data fusion achieves a higher perceived Capacity, it also achieves a higher False Capacity. From the analysis in this subsection it can be seen that the use of Data Fusion although reducing substantially the perceived capacity, also minimizes the False Capacity. This occurs because the probability of detection and false alarm are dependent of each other; in fact it is possible to express them as a function of each other. Therefore, as seen in the previous figures, by minimizing one the other is also minimized, since their relationship is of direct proportionality, although this relationship can be altered so that they become more robust against the effect of the other.

The Data Fusion schemes employed, perform the data fusion of the sensing results of all the cluster nodes, so hypothetically by using a subset of these nodes to perform the data fusion, it might be possible to increase the achieved capacity while minimizing the False Capacity. This will be made apparent in the next sub-section, where we study the effect of the number of network nodes on the system perceived capacity.

3.2 Effect of number of network nodes on system capacity

Here we study the effect of varying the number of network nodes participating in the cooperative spectrum sensing scheme. The simulation parameters are the same as in the previous subsection, and the only difference is that here we set the average correction index to be 0.2, and we vary the number of sensing nodes instead.

From **Figure 8** it can be seen that the potential capacity, C_{r}, achievable by the cooperative spectrum sensing mechanism decreases with the increase of the average correlation index, i.e., the more correlated are the nodes the lower is the probability of the nodes to be experiencing different conditions, leading to less opportunities to find available resources. The potential capacity is therefore a function of the spatial diversity degree. In **Figure 12** and **Figure 13** are depicted the Capacity and False Capacity versus the number of network nodes, respectively.

From **Figure 12** it is observed that C_{s} is constant when increasing the number of nodes, while the C_{df} decreases. The decrease of C_{df} is explained by the data fusion reducing the spatial diversity, and therefore the more nodes are performing data fusion, the less is the perceived capacity. The increase of the number of nodes leads to an increase of the overall probability of false alarm on data fusion schemes, which causes the system’s perceived capacity to decrease. This becomes evident when considering the OR rule, since in this scheme the probability of false alarm increases with the number of nodes participating in the data fusion, as shown in the **Table 1**.

From **Figure 13** is observed that the FC_{s} is constant with respect to the increase of the number of nodes, while the FC_{df} decreases with the number of nodes, which is explained by the decrease of the missed detection probability. This occurs because the purpose of using data fusion schemes is to increase the chances of performing a detection, which is what we observe in **Figure 13**.

The study presented in this subsection confirms the hypothesis formulated before, that the use of a lower number of nodes in the data fusion increases the system’s perceived capacity, but it also increases the false capacity.

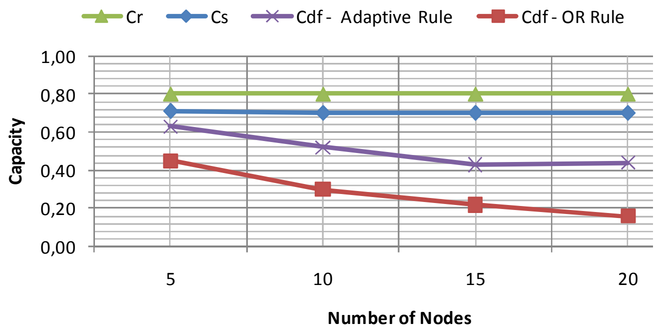

Figure 12. *Capacity vs. number of network nodes, with mean correlation index 0.2*

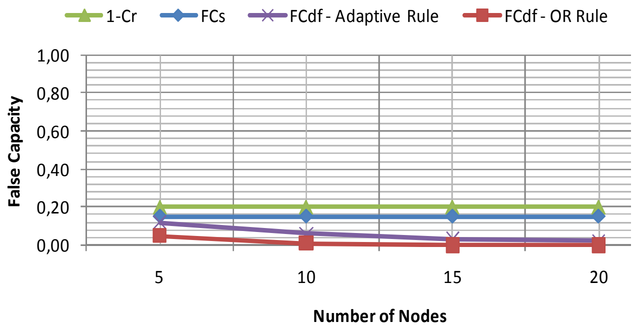

Figure 13. *False capacity vs. number of network nodes, with mean correlation index 0.2*

3.3 Effect of channel occupation on system capacity

In the previous sub-sections it was observed how the system perceived capacity varies with the average correlation index and with the number of nodes. In this subsection we study the effect of varying channel occupation statistics. The simulation parameters are the same as in the previous subsections except that we consider 0.2 and 0.5 average correlation index and we vary the transmitters duty cycle.

In **Figure 14** and **Figure 15** we illustrate respectively the Capacity and False Capacity versus the channel occupation, i.e., the transmitters duty cycle. In **Figure 14** we can observe that the perceived capacity decreases with the increase of the channel occupation, as expected since if the channel is occupied an higher percentage of the time then the potential system's capacity will therefore be lower. The reason the C_r is not 0 when the duty cycle is 1 because that some of the nodes are outside the coverage of the transmitter, i.e., the signal is below the *SNR* detection threshold, so even if the transmitter is ON they can still experience the channel as free. The opposite trend can be seen in **Figure 15**, where the False Capacity increases with the channel occupation, which is expected since a missed detection, can only occur if there is a signal being transmitted.

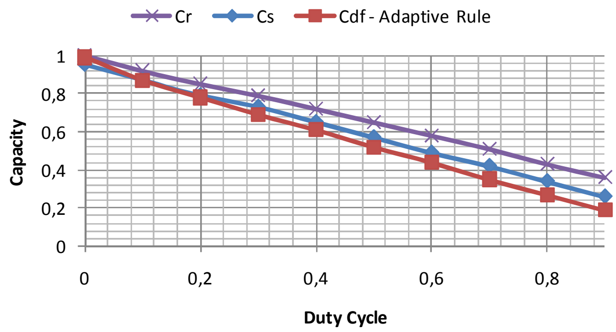

Figure 14. *Capacity vs. channel occupation, average correlation index 0.5 and 20 cluster nodes*

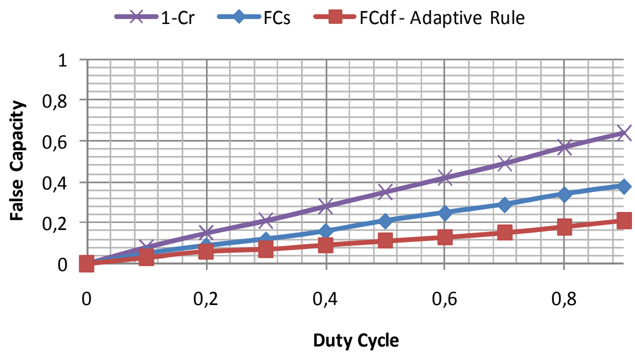

Figure 15. *False capacity vs. channel occupation, with mean correlation 0.5 and 20 cluster nodes*

It should also be noted that although the perceived and potential capacity decreases linearly, its inclination is dependent of the environment correlation. This can be observed by comparing **Figure 14** with **Figure 16**.

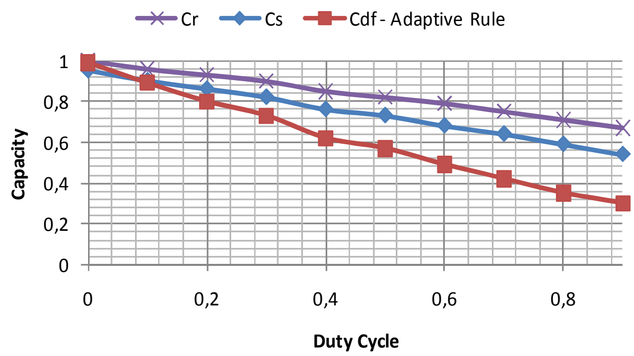

Figure 16. *Capacity vs. Channel Occupation, with mean correlation 0.2 and 20 cluster nodes*

3.4 Considerations on how to increase system capacity

From the analysis performed in the previous subsections it can be concluded that the environment correlation affects the potential capacity achievable by a cooperative spectrum sensing mechanism. The effect depends on how the sensing results are used, from the analysis it can be seen the capacity is higher when not using data fusion schemes while the false capacity is lower when using data fusion schemes.

Another observation is that the increase of the number of nodes participating in a data fusion scheme reduces the perceived Capacity, while also reducing the False Capacity. From this study the main conclusion drawn is that by using a lower number of nodes in the data fusion it might be possible to achieve a higher perceived capacity, while the minimization of the False Capacity will depend of the data fusion scheme in place.

How this can happen, will be accomplished doing the data fusion with a lower number of nodes, in a sub-set of the available nodes, and if the perceived capacity will be maximized while the false capacity will be minimized will depend how these sub-set will be defined. Most likely this will happen when these sub-sets are comprised of nodes with the same degree of correlation, not average correlation.

4. Conclusion

In this paper, we analyzed how the perceived capacity of a cooperative spectrum sensing mechanism behaves, according to the experienced environment correlation, channel occupation and number of cooperating nodes. The analysis was made based on the defined metrics which characterize the perceived Capacity and False Capacity achieved by the studied schemes on all parts of the data fusion chain.

From this study, it was concluded that for data fusion schemes to be used, they cannot perform the data fusion on the results of all the sensing nodes, and therefore need to be subdivided in smaller subsets nodes. This will result according to the observed results on a higher perceived Capacity while minimizing the False Capacity.

The future steps of this work will be to define a data fusion algorithm which works with subsets of the available nodes for sensing, therefore potentially increasing the perceived capacity, where these subsets can be created based on the pair wise correlation between the nodes.

References

[1] J. MITOLA III – *Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio*, Ph.D. Thesis, Royal Institute of Technology (KTH), Stockholm, Sweden, May 2000

[2] I.F. AKYILDIZ, W.Y. LEE, M.C. VURAN, S. MOHANTY – *NeXt Generation/Dynamic Spectrum Access/Cognitive Radio Wireless Networks: A Survey*, Computer Networks, Vol. 50, No. 13, pp. 2127-2159, Sep. 2006

[3] Z. QUAN, S. CUI, H. POOR, A. SAYED – *Collaborative Wideband Sensing for Cognitive Radios*, IEEE Signal Processing Magazine, Vol. 25, No. 6, pp. 60-73, Nov. 2008

[4] P.K. VARSHNEY – *Distributed Detection and Data Fusion*, Springer-Verlag, New York, NY, 1997

[5] H. KIM, K.G. SHIN – *Efficient Discovery of Spectrum Opportunities with MAC-Layer Sensing in Cognitive Radio Networks*, IEEE Transactions on Mobile Computing, Vol. 7, No. 5, pp. 533-545, May 2008

[6] H. URKOWITZ – *Energy Detection of Unknown Deterministic Signals*, Proceedings of the IEEE, Vol. 55, No. 4, pp. 523-531, Apr. 1967

[7] D. CABRIC, A. TKACHENKO, R.W. BRODERSEN – *Experimental Study of Spectrum Sensing Based on Energy Detection and Network Cooperation*, Proc. of the 1st International Workshop on Technology and Policy for Accessing Spectrum, TAPAS '06, Boston, MA, Aug. 5, 2006

[8] A. GHASEMI, E.S. SOUSA – *Collaborative Spectrum Sensing for Opportunistic Access in Fading Environments*, Proc. of the 1st IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN 2005, pp. 131-136, Baltimore, MD, Nov. 8-11, 2005

[9] E. VISOTSKY, S. KUFFNER, R. PETERSON – *On Collaborative Detection of TV Transmissions in Support of Dynamic Spectrum Sharing*, Proc. of the 1st IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN 2005, pp. 338-345, Baltimore, MD, Nov. 8-11, 2005

[10] S.M. MISHRA, A. SAHAI, R.W. BRODERSEN – *Cooperative Sensing among Cognitive Radios*, Proc. of the IEEE International Conference on Communications, ICC '06, pp. 1658-1663, Istanbul, Turkey, Jun. 2006

[11] S.Y. TU, K.C. CHEN – *General Spectrum Sensing in Cognitive Radio Networks*, CoRR, Jul. 2009, http://arxiv.org/abs/0907.2859

[12] N. PRATAS, N. MARCHETTI, N.R. PRASAD, A. RODRIGUES, R. PRASAD – *Centralized Cooperative Spectrum Sensing for Ad-Hoc Disaster Relief Network Clusters*, Proc. of the IEEE International Conference on Communications, ICC 2010, pp. 1-5, Cape Town, South Africa, May 23-27, 2010

[13] N. PRATAS, N. MARCHETTI, N.R. PRASAD, A. RODRIGUES, R. PRASAD – *Decentralized Cooperative Spectrum Sensing for Ad-Hoc Disaster Relief Network Clusters*, Proc. of the IEEE 71st Vehicular Technology Conference, VTC 2010-Spring, pp. 1-5, Taipei, Taiwan, May 16-19, 2010

[14] N. PRATAS, N. MARCHETTI, A. RODRIGUES, R. PRASAD – *Capacity Limits Introduced by Data Fusion on Cooperative Spectrum Sensing under Correlated Environments*, Proc. of the 8th International Conference on Communications, COMM 2010, pp. 497-502, Bucharest, Romania, Jun. 10-12, 2010

[15] N. PRATAS, N. MARCHETTI, N.R. PRASAD, A. RODRIGUES, R. PRASAD – *Adaptive Counting Rule for Cooperative Spectrum Sensing under Correlated Environments*, Proc. of the 13th International Symposium on Wireless Personal Multimedia Communications, WPMC 2010, Recife, Brazil, Oct. 11-14, 2010

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