Clustered Hybrid Energy-aware cooperative Spectrum Sensing (CHESS)

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***Abstract*—This work proposes a novel algorithm for energy-efficient and reliable spectrum sensing in a cognitive network. The algorithm relies on cooperation between secondary devices, that organize themselves in clusters defined according to both sensing reliability and energy efficiency. The proposed algorithm is compared by means of computer simulations with a simpler, non cluster-based cooperative sensing scheme. Simulation results highlight that the adoption of an energy-efficient, sensing-aware clustering algorithm in the sensing procedure can significantly improve both sensing reliability and network lifetime in secondary cognitive networks.**

I. Introduction

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 typically been achieved by 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 [1].

Important technical challenges still need to be overcome, however, in order to achieve successful coexistence and cooperation among heterogeneous systems. Spectrum sensing, in particular, is a key research topic in order to enable unlicensed networks to coexist with primary users [2]. In this context, the stringent requirements on sensing accuracy and reliability for devices forming a cognitive network are often impossible to meet for a single device. Figure 1 shows a scenario where a cognitive device is required to determine the presence of a primary transmission from a distance larger than the nominal coverage range of the transmitter. Failure to detect the presence of such transmitter may potentially lead to interference to primary receivers located at the the edge of the coverage area. Even in more favourable topologies, the sensing accuracy of a single device is affected by propagation effects such as fading and shadowing, potentially leading to missed detections of an active primary transmitter and, as a consequence, to the introduction of harmful interference. In order to address the above issue, several research groups investigated in the last few years the possibility of introducing cooperation in the sensing function.

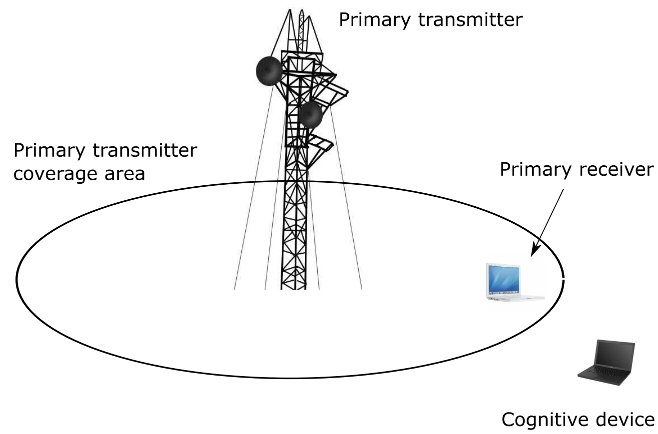

Fig. 1. Example of sensing scenario in which a cognitive device is required to perform sensing on a signal outside the nominal coverage area of the primary transmitter.

The most straightforward solution to introduce cooperation in sensing was proposed in [3]. The authors consider a network of *n* devices sensing the environment by means of an energy-detection receiver, and propose to combine the individual decisions of the devices according to an OR rule, leading the whole network to decide that a primary is present if any of the devices decides so. Assuming that each individual device is subject to independent fading/shadowing leading to the same average SNR, so that all devices are characterized by the same average probabilities of false alarm P_{fa} and of detection P_d, the corresponding probabilities for the whole network are the following:

$$\begin{cases} Q_{fa} = 1 - (1 - P_{fa})^n \\ Q_d = 1 - (1 - P_d)^n \,. \end{cases} \tag{1}$$

The overall effect is thus to increase the probability of detection at the price of an increased probability of false alarm.

A more refined cooperation scheme is proposed in [4] for a network composed of two users that send data to a Base Station (BS). The approach proposed in [4] relies on the adoption of a Time Division Multiple Access scheme, as shown in Figure 2. Each cognitive user transmits for two consecutive slots and then listens for the next two. The

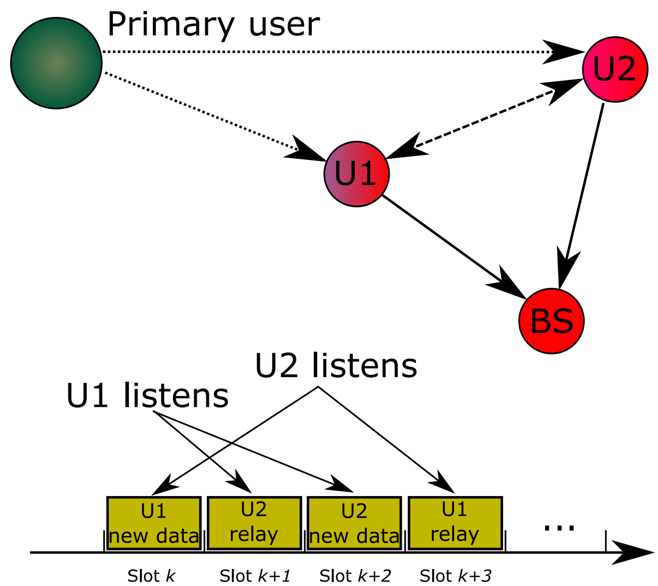

Fig. 2. Cooperation scheme proposed in [4] for a two users network. Signal relayed by user U1 also includes the signal transmitted by the primary user and overlapping to the signal transmitted by the user U2. By listening to the signal relayed by U1, U2 can subtract its own signal and improve the probability of detecting the signal transmitted by the primary user, leading to an overall improvement in detection probability.

cognitive user uses the first of the two slots to retransmit the signal received in the last listening slot, according to an Amplify and Forward (AF) scheme (with reference to Figure 2, U2 will retransmit in slot *k+1* the signal received while listening in slot *k*), and the second one to send new data (e.g. user U2 in slot *k+2*, with reference to Figure 2). It is shown in [4] that the above scheme increases the probability of detecting a primary user by the cognitive network, and in particular by the user that receives a weaker signal from the primary user due to bad propagation conditions. In turn, the time taken by the cognitive network to free the wireless medium when a primary user shows up is reduced as well. The approach is extended to the case of an arbitrary number of cognitive devices in [5], where a pairing scheme between users characterized by unfavourable channel conditions and relay nodes that apply the AF scheme is proposed. The approach in [5] poses however scalability issues, due to the need of pairing devices with the corresponding relays by means of explicit help requests.

The scheme originally proposed in [3] requires the transmission of the *n* individual decisions to a Common Receiver in charge of taking the network decision according to the OR rule. Equivalently, one of the *n* devices can play the role of Common Receiver, thus only requiring *n-1* transmissions from the other devices. In both cases, the strategy is subject to the quality of the channel between the devices and the Common Receiver, since errors can be introduced during transmission of individual decisions. In order to overcome such issue, a network organization based on clusters has been proposed in [6]. In this work, cognitive devices are organized in clusters and, within each cluster, the device with the best communications channel towards the common receiver is selected as ClusterHead (CH). The network decision is thus obtained as a two steps process, in which a cluster decision is first obtained by combining the observations of all devices in the cluster at the CH, and then cluster decisions are combined at a common receiver again according to an OR rule. Different combination rules are compared at the cluster decision level, and it is shown that the proposed cluster-based approach outperforms the simple OR rule approach, in particular when a low Q_{fa} is required. The clustering approach proposed in [6] is a very interesting solution to the cooperative sensing problem, but it should be noted that the clustering criterion is not explicitly defined and, most important, neither the definition of clusters nor the selection of the CHs is related to the sensing capabilities of the nodes. Moving from the above analysis, in this work a novel scheme for cooperative spectrum sensing based on clustering that takes into account sensing performance in cluster formation and CH selection, referred to as *Clustered Hybrid Energy-aware cooperative Spectrum Sensing (CHESS)*, is proposed. The scheme adopts a hybrid clustering approach that combines sensing reliability and energy efficiency. The goal of the *CHESS* scheme is to improve the accuracy of the sensing phase compared to standard, non-clustering-based solutions, while increasing energy efficiency and in turn extending network lifetime. The *CHESS* scheme is compared with the cooperation scheme without clustering proposed in [3], while future work will address the comparison with alternative approaches based on clustering, such as the one proposed in [6].

The paper is organized as follows. Section II describes the proposed sensing algorithm. Section III presents simulation results comparing the *CHESS* scheme with the solution for cooperative clustering proposed in [3], based on cooperation without network clustering, in terms of both sensing reliability and energy efficiency. Finally, Section IV draws conclusions.

II. Clustered Hybrid Energy-aware cooperative Spectrum Sensing (CHESS) algorithm

The two key aspects taken into account in the design of the proposed scheme are:

- *Sensing reliability*: the secondary network should minimize the interference generated towards primary users.
- *Energy efficiency*: the secondary network should minimize energy consumption for sensing operations and for its normal activity in order to maximize its lifetime.

The network scenario considered for the secondary network is the same considered in [3], and is composed of a set of cognitive nodes scattered in random positions, sending information to a Base Station (BS) that coordinates network activities, as shown in Figure 3. Furthermore, it is assumed that secondary data traffic interferes with primary activity, while sensing and control traffic in the secondary network is sent on a separate, low-speed, interference-free channel.

The *CHESS* algorithm leads to the partition of the nodes in the secondary network in clusters, each cluster being managed

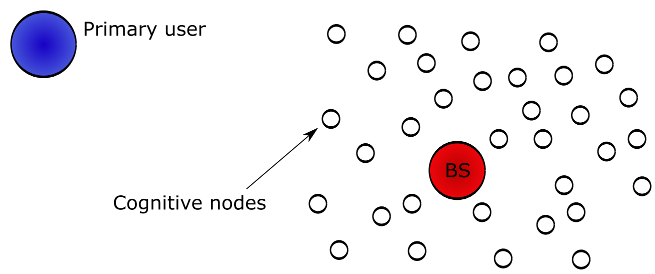

Fig. 3. Network scenario considered in the design of the CHESS algorithm.

by a CH. The CH is in charge of performing the sensing operation and of forwarding data traffic generated by nodes in the cluster to the BS. A secondary network operating in accordance to the *CHESS* algorithm can be in one of three possible states:

- *Training* - while in this state, secondary nodes evaluate their reliability in sensing the presence of the primary user, in order to determine the nodes that are most suitable to act as CHs;
- *Clustering* - while in this state actual cluster formation and CH selection take place;
- *Activity* - while in this state the secondary network operates normally, with nodes sending data to the BS through the CHs.

1) Training: The network moves in the *Training* state following the transmission of a broadcast *Training start* packet by the BS. The packet includes the time $T_{training}$ to be spent in this state, and the information required to define a slotted time axis. Each slot is divided in three parts: a *beacon* part, a *sensing* part and a *reporting* part. For the duration of the $T_{training}$ time the following procedure is applied:

1) in the *sensing* part of each slot all nodes carry out sensing and take an individual decision on the presence of the primary;
2) in the *reporting* part of each slot nodes transmit their decisions to the BS adopting a CSMA access technique;
3) in the *beacon* part of each slot the BS broadcasts the network decision on the presence of the primary based on the inputs received from the nodes in the previous slot. The decision is obtained on the basis of the individual decisions according to a majority rule;
4) each node compares the majority decision with its individual one, and in case the two decisions are in agreement, the node increases a counter measuring the number of correct decisions;
5) at the end of the training each node evaluates a reliability parameter R, obtained as the ratio between the number of correct decisions and the total number of taken decisions.

2) Clustering: The network moves into the Clustering state following the transmission of a broadcast *Clustering start* packet by the BS. Following the reception of the packet each node measures its suitability to play the role of CH by evaluating the following parameter:

$$\Lambda = \epsilon \cdot \frac{E_{residual}}{E_{start}} + \rho \cdot R, \tag{2}$$

where:

- ϵ and ρ are weighting coefficients for the energy and sensing reliability aspects, respectively;
- $E_{residual}$ and E_{start} are the remaining energy and the initial energy of the node, respectively.

Next, nodes apply a distributed algorithm for the selection of the CHs and the formation of the clusters. The expected size of the clusters is determined by setting the value of the transmitted power, which is thus considered as a system parameter. The selected value is referred to as *intra-cluster* power level. The cluster formation algorithm can be described as follows:

1) each node with $\Lambda \geq \Lambda_{min}$ repeatedly transmits a *Tentative CH* packet, including its address and its value of Λ;
2) upon receiving a *Tentative CH* packet, a node compares the received value of Λ with its own;
3) if the received value of Λ is larger than its own, the receiving node stops sending *Tentative CH* packets since at least one better CH candidate is within its range, and waits for the procedure to finish;
4) when a predefined time for *Tentative CH* transmission, communicated in the *Clustering start* packet, is over, nodes that did not stop transmitting the packets are the best candidates to become CHs, and transmit a *Final CH* packet, declaring themselves as CHs;
5) nodes that did not declare themselves as CHs and receive one or more *Final CH* packets select the best CH in range and join its cluster;
6) nodes that did not declare themselves as CHs but do not receive any *Final CH* packet elect themselves CHs. Note that such nodes could have a $\Lambda \leq \Lambda_{min}$.

3) Activity: After the clustering procedure is completed the network enters in the *Activity* state, following a broadcast *Activity start* packet by the BS.
Network operation in this state is still organized based on a slotted time axis, but nodes behave differently depending on their role:

- Standard nodes send their DATA packets to their CHs at the intra-cluster power level;
- CHs relay DATA packets received from standard nodes to the BS at full power;
- Additionally, CHs that meet the $\Lambda \geq \Lambda_{min}$ condition perform sensing and report their decision to the BS.

At the beginning of each slot the BS broadcasts the decision on the presence of the primary to the whole secondary network. Whenever the BS reports the channel as BUSY, all nodes stop transmitting DATA packets, while CHs keep on transmitting sensing packets to the BS on the dedicated control channel. When the channel is reported as IDLE for a minimum number N_{IDLE} of consecutive slots, the network reverts to normal

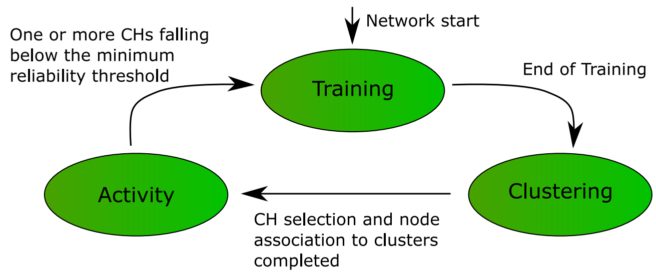

Fig. 4. Possible states for the secondary network in the CHESS algorithm, and events leading to state changes.

operation and nodes start transmitting and relaying DATA packets.
While in *Activity* state, CHs keep on evaluating the value of their Λ parameter. Whenever a CH determines that its Λ fell below a predefined threshold it sends an alarm packet to the BS, which will force the network back to the *Training* state by broadcasting a *Training start* packet by the BS, moving next to the *Clustering* state and eventually back to the *Activity* state with a new cluster organization. The relationships between states and the events leading to state changes in the secondary network are presented in Figure 4.

III. Simulation Settings and Results

In order to prove the effectiveness of the CHESS algorithm described in the previous section, a simulator was created in the framework of the OMNeT++ simulation environment [7], enhanced with the adoption of the Mobility Framework proposed in [8]. A simulation scenario characterized by a playground of 1000x1000 square meters, where a variable number N of secondary nodes send data traffic to a BS for a simulation time T_{sim} was considered. Simulation results were averaged over N_{runs} runs. The scenario is characterized by the presence of a primary transmitter alternating activity periods and silence periods with average durations $T_{activity}$ and $T_{silence}$, respectively; activity periods were furthermore characterized by introducing an activity factor denoted as *AF*. As already stated in Section II, secondary data traffic interferes with primary activity, while secondary sensing and control traffic is sent on a dedicated interference-free channel. Table I summarizes the key simulation parameters.
The assumption is made that the channels between the primary transmitter and the secondary nodes are affected by *Rayleigh* fading, whereas channels are of *AWGN*-type for secondary networks. It is furthermore assumed that secondary nodes use an energy detection approach for spectrum sensing.
Under the above assumptions false alarm probability P_{fa} and detection probability P_d for individual sensing at each secondary node can be evaluated using the relations presented in [9].
The parameters characterizing the secondary nodes are listed in Table II. Table III contains the considered data traffic generation parameters for the secondary network, while Table IV displays the values of the most relevant parameters involved in the sensing and clustering procedures. Note that the balance between sensing and energy reliability was tilted towards energy by choosing $\epsilon > \rho$, in order to avoid too many alarms triggered by slight energy variations. The impact of different settings for ϵ and ρ coefficients is left for future work.

The *CHESS* scheme was compared in the above simulation scenario with the simple solution for cooperative clustering proposed in [3], and referred to in the following as *Basic* sensing algorithm. The Basic sensing algorithm implements the scheme proposed in [3] by adopting a TDMA scheme characterized by a slotted time axis, with slots of duration T_{slot} organized in frames composed of N_{slots} slots. The algorithm requires each node to sense the channel in a different time

TABLE I
Simulation Scenario Parameters

Parameter	Value(s)
playground size	1000x1000 m^2
number of secondary nodes N	20; 30; 40; 50
simulation time T_{sim}	5 to 15 hours
simulation runs N_{runs}	10
primary Tx power	126 mW
primary $T_{activity}$	60 s
primary $T_{silence}$	15 s
primary *AF*	75%
primary carrier frequency	3.5 GHz
primary bandwidth	20 MHz

TABLE II
Secondary Node Parameters

Parameter	Value(s)
carrier frequency	3.5 GHz
bandwidth	20 MHz
full transmit power	20 mW
intra-cluster transmit power	0.6 mW

TABLE III
Traffic Parameters

Parameter	Value
data packet size	980 bits
packet generation period	0.25 s
bit rate	250 kb/s

TABLE IV
Sensing and Clustering Parameters

Parameter	Value(s)
Sensing and clustering message size	184 bits
ϵ	0.7
ρ	0.3

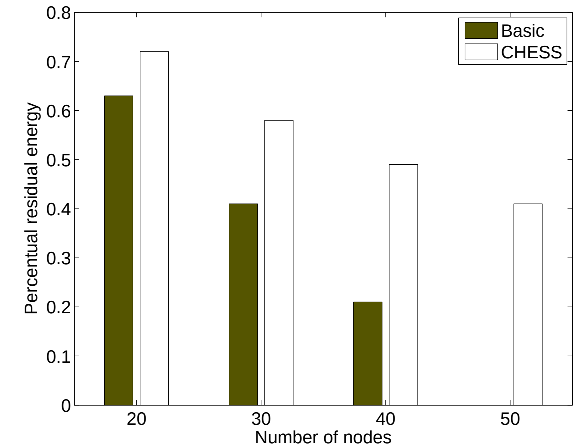

Fig. 5. Percentual residual energy per node for the CHESS vs. Basic sensing algorithms after 5 hours of operation. In a network of 50 nodes the Basic algorithm leads to a complete exhaustion of energy for all network nodes.

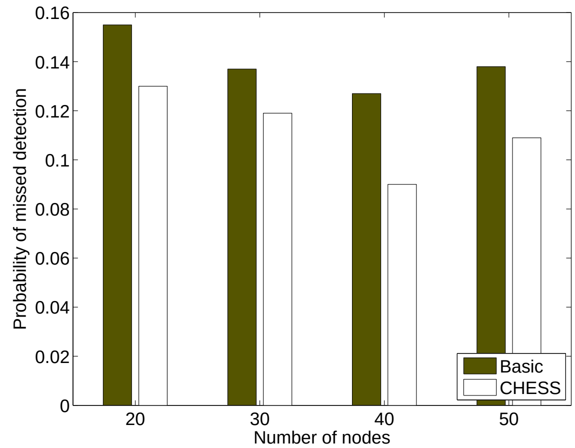

Fig. 7. Probability of missed detection for the CHESS vs. Basic sensing algorithms.

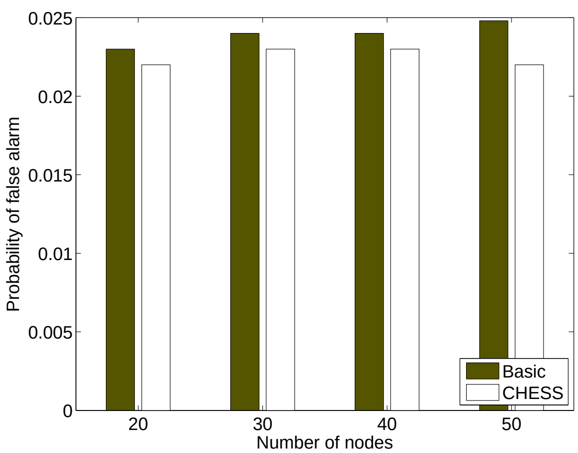

Fig. 6. Probability of false alarm for the CHESS vs. Basic sensing algorithms.

slot, and to send its decision back to the BS. The BS will then inform the whole network about the channel status, stopping network operations as soon as a node reports the channel as busy due to primary activity, thus applying an OR rule. Each node will be therefore required to perform sensing every $N_{slots} \cdot T_{slot}$, and it will be free to send data in the remaining time.

The CHESS vs. Basic schemes were compared in order to evaluate the impact of clustering on sensing accuracy and network performance. Figure 5 compares the two algorithms in terms of mean residual energy per CR node. The CHESS algorithm requires only one node per cluster to perform the sensing procedure, leading to a significant reduction in energy consumption compared to the case of the Basic algorithm, for which a constant sensing activity and subsequent transmissions are required for each node in the network. Furthermore, the adoption of a lower transmit power in the communications between nodes and CHs leads to an additional reduction in energy consumption. Procedures for re-clustering carried out on request of CHs that are running out of energy help increasing the lifetime of all nodes. In particular, the increase in energy efficiency is remarkable for large number of nodes, where the CHESS algorithm leads to an average residual energy per node close to 45%, while in the case of the Basic algorithm nodes have no energy left after five hours of operation.

The accuracy of the two algorithms in sensing the presence of primary activity is analyzed in Figures 6 and 7. Figure 6 shows that the adoption of the clustering approach proposed in the CHESS algorithm leads to a performance improvement in terms of false alarm probability, thus improving the efficiency in spectrum utilization by the secondary network. Most importantly, Figure 7 shows that the CHESS algorithm also leads to a significant reduction in the probability of missed detection, thus improving the coexistence capability of the secondary network by reducing the interference towards potential primary receivers. This result is due to the role played by the reliability parameter *R*, that measures how much the current node is reliable in detecting the primary activity. As explained in Section II each node measures its reliability level when the network is in the *Training* state, by comparing its decisions with the ones taken by the BS (majority rule). The value of *R* may vary in time leading, if necessary, to a new clustering procedure requested by one or more CHs.

Finally, Figures 8, 9 and 10 analyze the impact of the two algorithms on packet transmission. Figure 8 shows that the CHESS algorithm leads to a lower percentage of generated packets actually being transmitted. This can be explained if one considers that the CHESS algorithm leads to an improved detection performance compared to the Basic one. As a consequence a smaller percentage of packets are sent during primary activity, as presented in Figure 9. Additionally, Figure 10 presents the percentage of sent packets that are correctly delivered without creating interference on the primary, and

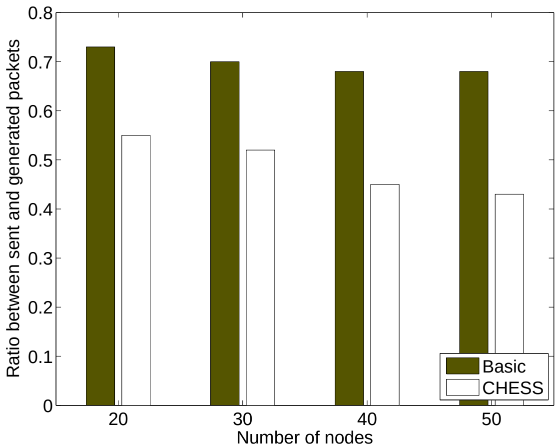

Fig. 8. Percentage of generated messages actually sent for the CHESS vs. Basic sensing algorithms.

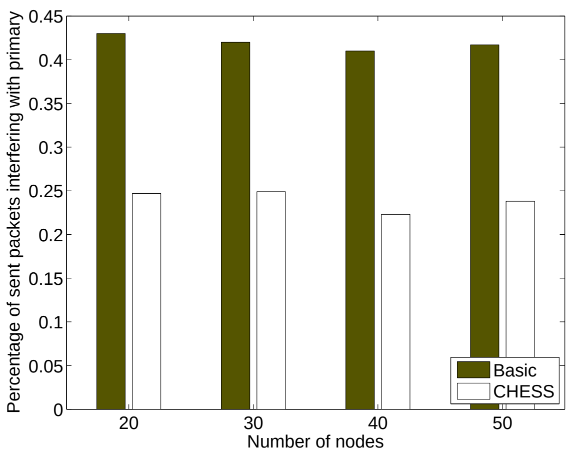

Fig. 9. Percentage of Sent data messages that interfere with primary transmission for the CHESS vs. Basic sensing algorithms.

shows that the CHESS algorithm is characterized by a higher percentage of correctly delivered messages, without taking into account packets that are sent during primary activity. It should be noted that in the present implementation of the CHESS algorithm the CH stops transmission activity for the entire cluster as soon as it detects the channel as BUSY. This conservative approach maximizes the coexistence capability of the secondary network; on the other hand, trusting the CH and stopping cluster operations before a network decision is taken can penalize secondary network performance when the CH decision proves to be wrong.

IV. Conclusion

In this paper a novel cooperative sensing algorithm based on a hybrid clustering approach combining energy and sensing accuracy, named CHESS, was proposed. The proposed algorithm was compared with the cooperative sensing scheme proposed in [3], where the decisions of the secondary nodes are combined by applying an OR rule. Simulation results show that the proposed scheme improves both network lifetime and sensing accuracy, by reducing the energy consumption and the probabilities of missed detection and false alarm. Results suggest thus that cooperation and clustering lead in general to a significant performance improvement that allows a secondary network to better coexist with a primary user.

Simulation results also indicate that the proposed CHESS algorithm leads to a lower number of sent data packets if compared to the Basic algorithm. As already pointed out in Section III, this is due to the conservative approach taken by CHs, stopping their clusters whenever they sense the channel as BUSY. In this view, future work will investigate alternative approaches in the management of sensing activity within a cluster. The analysis of the impact of cluster radius and node density on network performance will be investigated as well.

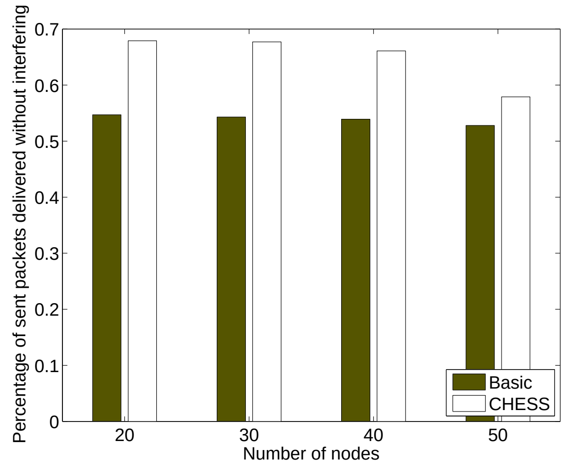

Fig. 10. Percentage of Sent data messages that are correctly delivered without interfering with primary transmission for the CHESS vs. Basic sensing algorithms.

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