Cluster-Based Spectrum Sensing Architecture for Opportunistic Spectrum Access Networks

Przemysław Pawełczak, Cheng Guo, R.Venkatesha Prasad, and Ramin Hekmat
Faculty of Electrical Engineering, Mathematics and Computer Science
Delft University of Technology, Mekelweg 4, 2600 GA Delft, The Netherlands
Email: {p.pawelczak, c.guo, vprasad, r.hekmat}@ewi.tudelft.nl

Abstract— **In opportunistic spectrum access networks (OSAN) procedures for spectrum sensing have to be designed in such a way that the probability of miss-detection and false alarm, should not exceed a certain level, while detecting the presence of the licensed user (LU) of a radio channel. One of the approaches - that minimizes the error in detection - is to combine measurements from various nodes within an OSAN. Here we propose a TDMA-based protocol for exchange and management of spectrum sensing data, that exploits cooperative sensing. Our work is accompanied by the analysis of the effects of node mobility during the contention of nodes for channels in our protocol. We present a comprehensive study of an OSAN system.**

I. INTRODUCTION

As one can notice, frequency plans of various countries leave minimal or no space for the assignment of new wireless services (for example see [1]). However, recent measurements have shown that the vast number of spectrum bands are rarely or seldom occupied [2]. Therefore to keep up with the growing demand for bandwidth many independent academic and standardization institutions are considering the concept of Opportunistic Spectrum Access (OSA) as a promising candidate for future radio access. Radios employing OSA can access parts of radio frequency spectrum for which they do not have proprietary rights under the condition that they cause the least interference to the Licensed User (LU) of that band. Access to LU bands can be done on the transmit power control basis (such as spread spectrum or ultrawideband communication) or using ”Listen Before Talk” principle.

A network or a system employing the OSA for enhancing the available bandwidth is referred to as an Opportunistic Spectrum Access Network (OSAN). Due to the fact that signals received from LU is subjected to fading and noise, many authors have concluded that the highest performance of spectrum sensing in an OSAN is achieved through cooperation amongst independently located sensing nodes [3]–[6]. However without the information about the availability of spectrum from other parties, such as networks, external sensors or spectrum regulators, an OSAN has to depend only on the detection management using its own nodes. Therefore, there is a need for an architecture and an accompanying protocol aiming specifically at collecting, fusing and exchanging spectrum sensing data within an OSAN.

Specifically, we propose an architecture extending our prior work [7], where we have analyzed the protocol in which the consecutive periods of energy detection are independently accomplished by a subset of OSAN nodes. In each time slot different sets of nodes scan the spectrum and immediately transfer sensing data to a *central detection entity*, which then makes a decision about availability of the channel. In our sensing architecture an OSAN is divided into clusters, where each cluster is managed and represented by a Cluster Head (CH). Nodes from each cluster scan the spectrum at the same time and then send data to CH in slots of a frame assigned to them. All CHs will exchange spectrum measurements with other CHs, and make decisions about the presence of LU on each scanned channel. Later, each CH will respond back to its OSAN nodes leading to a network-wide decision on the availability of each LU channel.

Since the nodes move in the OSAN operational zone, a constant change in availability of nodes in the cluster may make sensing and decision process a difficult chore. Thus we focus on obtaining the level of node density in each cluster, such that the probability of scheduling a sensing task to a node which no longer exists in the cluster is minimized. We present initial performance analysis of the protocol and also analyse the effect of mobility on the contention for joining a cluster when the nodes move.

This paper is organized as follows. In Section II network model and sensing data exchange protocol is presented. Section III deals with the analysis of movement of sensing nodes and their impact on the detection process. Finally in Section IV we conclude.

II. COOPERATIVE LU DETECTION ARCHITECTURE

An OSAN cooperatively detects the absence of LUs in the set $\mathbb{M}$ of M radio channels, by means of energy detection [8]. The channel is observed for t_{int} seconds. We call this a frequency scanning process. For the sake of simplicity, we neglect other signal detection techniques, such as those based on the feature detection – which are limited to only for the cases when an OSAN knows radio features of the detected LU signal or where interaction between OSAN and the LU is allowed by means of spectrum etiquette. We assume that

This research was carried out in the Adaptive Ad-Hoc Free Band Wireless Communications (AAF) project funded by the Freeband program of the Dutch Ministry of Economic Affairs.

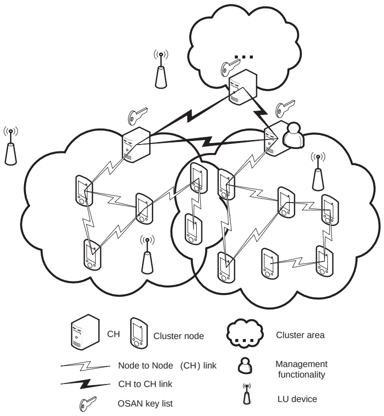

Fig. 1. A functional architecture of an OSAN.

LU does not change state during observation and an OSAN can distinguish whether channel $m \in \mathbb{M}$ was used by LU or OSAN itself.

The OSAN consists of a set $\mathbb{N}$ of N nodes, each having the capability to sense channels. This means that each node is equipped with two separate radio front-ends: one responsible for data communication within an OSAN, and the other for spectrum sensing [9]. All OSAN nodes, except for CH, have limited energy. Therefore, the protocol has to assign sensing cycles such that it will not force one subset of $\mathbb{N}$ to scan excessively thereby load balancing. Thus in each sensing frame different subsets $\mathbb{K} \subset \mathbb{N}$ is gathering samples. During sensing phase nodes of an OSAN stay silent, so that energy detector will not misinterpret communication between OSAN nodes as the LU activity. The number of sensing nodes $|\mathbb{K}| = k_m$ is limited by the maximal number of slots in the protocol reserved for nodes-to-CH communication. Nodes in the operational area of OSAN are aggregated into C clusters, where each cluster is managed by a CH. Each CH contains the list of security keys of each OSAN node. Moreover one of the CHs will have a temporal management functionality for all CHs. After scanning, each sensing node communicates to its respective CH to inform it about the measured signal energy level. In the next phase all CHs exchange their measurements, thus all CHs can make the same decision about the presence of the LU, based on the set of Ck_{max} energy values. Decision is made by comparing the sum of the sensed energy levels with a threshold. Finally all CHs respond back to their OSAN nodes about the availability of the channels. The mobility of CHs is much smaller, compared to OSAN nodes, to be taken into account. In our architecture OSAN is synchronized, such that not only sensing, but whole communication between CH and nodes is performed using TDMA. An architecture for cooperative LU detection is depicted in Fig. 1. The following discussion aims at spectrum sensing protocol only, i.e. protocol for robust detection of spectral opportunities. We therefore do not focus on the analysis of protocol for data communication of OSAN, for which a distinct block is reserved in network superframe.

Our protocol aims at network-wide knowledge of presence of the LU on each of M channels, thus there is neither negotiation between CHs about which channels are free, nor forcing nodes to change their decision about spectrum occupancy, contrary to the approach proposed in [6]. We note that communication between nodes and CH and between different CHs is performed on a dedicated control channel which is not affected by the operation of any LU. The protocol we design should be used specifically in the bands, in which absence of presence of LU is distributed exponentially, consequently prediction of the presence of LU is difficult. See Appendix I for a sample of analysis of a real measurement.

A. *Structure of the Protocol*

Sensing data exchange is done in the following phases. First a guard band is allowed for clock synchronization between OSAN nodes. Then the nodes selected by each CH in the previous frame senses the set of frequencies for t_{int} seconds. After sensing period each node has a reserved slot in the frame of t_{nss} length to report to the CH about the observed energy level. Reports are sent in such a way that when a node reports to its CH all other nodes in that cluster and other clusters remain silent waiting for their turn. To guard against the errors during transmission each measured data is secured by Forward Error Correction (FEC) scheme (length of this part of the frame equals to $Ck_m t_{sss}$). We note that sometimes each cluster can have a smaller number of nodes than k_m. Therefore in cluster management phase (CMP) one of CHs will decide how to divide slots for all C clusters. We discuss this procedure later.

CH-to-CH communication phase is preceded by contention phase (CP), during which nodes moving from one cluster to the other register to a new cluster, e.g., sensing domain. A node decides to join a particular cluster based on the signal strength received from each CH.

In the next phase CHs send combined energy samples (summed and averaged) to other CHs. We assume that all CHs are within one hop reach of each other unlike normal OSAN nodes with sensing capability, where they can only reach CH with the best received signal strength. Combining the energy can be done by each CH in the periods between successive transmissions of nodes from other clusters and CP, thus we do not need to reserve additional slot for processing. Result of the computation together with the Newly Joined List (NJL) of nodes is broadcasted to other CHs. This part of the frame is also protected from errors by FEC (total size of the CH-to-CH frame is equal to t_{ccl}). We note that transmission takes place in slots to minimize the probability of losing data due to collision. We note that, since each CH receives information from other CHs it can combine measurements applying the same criteria and thus results consistant Channel Availability List (CAL) at all CHs. Moreover, using the NJL, each CH can update its node member list by removing all nodes that have been reported to have been joined by other CHs.

In the following phase one of the CHs, elected in the previous frame as OSAN Manager (MNG), decides how to divide

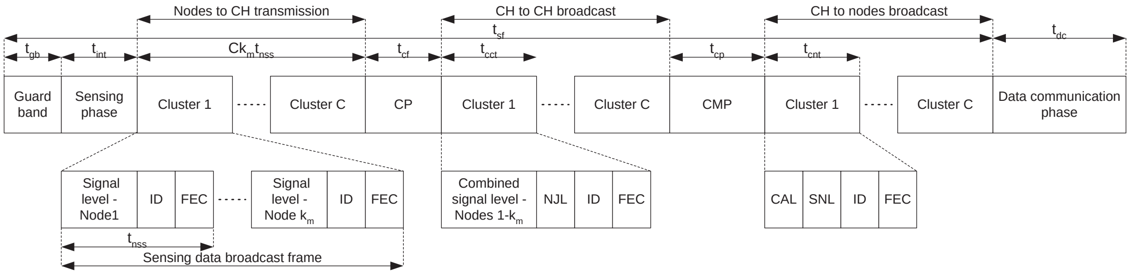

Fig. 2. Frame structure of the proposed spectrum data exchange protocol; CAL - Channel Availability List, CP - Contention Phase, CH - Cluster Head, CMP - Cluster Management Phase, FEC - Forward Error Correction, NLJ - Newly Joined List, SNL - Scheduled Nodes List.

sensing slots among all clusters. The non equal assignment of slots exists only when each cluster has $N_i < k_m$ nodes. Thus in this case MNG assigns additional slots to cluster that has at least $2k_m - N_i$ nodes. Together with this information MNG assigns and then transmits the IDs of all the nodes that will transmit in the next sensing frame. Each node is chosen with a probability $p(n) = 1/N$. Additionally, MNG schedules who is going to be the next MNG in OSAN. This scheduling can be performed randomly and usually will not change frequently. While all CHs receive information from MNG they automatically resend to their nodes within the frame containing CAL and SNL. Total time of this transmission is equal to t_{cnt} and is secured by FEC. At the end of the sensing protocol frame, data communication on distinct channels given by CAL is performed. The complete frame structure is depicted in Fig. 2.

III. Impact of Nodes Mobility on LU Detection Quality

In our proposed protocol nodes have to register first to a CH to take part in the sensing process. However due to the multiple access phenomenon during CP, some nodes will not be able to register successfully. The following analysis are performed under the assumption that the probability of not receiving an information from sensor due to transmission errors is negligible. We first derive the arrival rate $\lambda(t)$ of nodes contending for the cluster during time t. We assume the clusters of circular shape, and uniform distribution of nodes. When the nodes are moving randomly in each cluster having the size $N_C = N/C$, arrival rate can be found using (see Appendix II)

$$\lambda(t) = N_C\left(1 - \frac{2}{\pi}\left[\cos^{-1}(z) - z\sqrt{1-z^2}\right]\right), \qquad (1)$$

where R is the radius of the cluster, $d_f = vt$, is the distance traveled by the node with an average speed v during time t, and $z = \frac{d_f}{2R}$.

For the analysis we can assume two cases: 1) only the nodes that arrive during inter contention phase $t_{icf} = t_{dc} + t_{sf} - t_{cf}$ can contend for the channel, and 2) any arrival can contend for the channel (even those nodes that changed their position during CP, i.e., during $t_{tot} = t_{dc} + t_{sf}$). The analysis depends on the relation between t_{tot} and t_{cf}. Specifically if $t_{icf} \gg t_{cf}$ then, indeed, number of new arrivals came during CP can be assumed negligible. This also implies that, on the average, fixed number of packets will contend for the channel at the beginning of each CP. In case $t_{icf} \lessapprox t_{cf}$ then arrival traffic will be a sum of fixed aggregated stream of packets from t_{icf} and arrival of new registration packets in each slot of CP.

We analyze both cases using Slotted Aloha multiaccess protocol [10]. We note that Slotted Aloha assumption implies that all registration packets, containing node ID, have equal size. We also assume boundless OSAN operation area $\mathfrak{R}$. Given this foundation we assume that the average number of nodes within a cluster is always the same and equal to N_C.

A. Case 1 ($t_{icf} \gg t_{cf}$)

Analysis of multiaccess protocols can be divided into two based on whether the receiver (i.e., CH) has the ability to capture one packet in case of a collision. Let t_{sl} be the number of available slots during CP. In the capture case the best strategy is to force all buffered (during t_{icf}) registration packets to immediately contend for a slot. This assumption might be unrealistic from the physical point of view, however we can treat this result as an upper bound on the performance of our proposed protocol. Thus the average number of nodes that unsuccessfully contend for registration is

$$W_{1c} = \begin{cases} \lambda(t_{icf}) - t_{cp}/t_{sl}, & \lambda(t_{icf}) > t_{cp}/t_{sl} \\ 0, & \lambda(t_{icf}) < t_{cp}//t_{sl} \end{cases}. \qquad (2)$$

Without capturing ability of a CH, when nodes would immediately contend for the channel, all of them will experience collision. To resolve this problem the simple strategy is to randomly delay each buffered packet and transmit it with a probability $p_d = 1/\lceil\lambda(t_{icf})\rceil$. Whenever nodes experience collision, each colliding packet will again be transmitted with probability p_d until the first success. Therefore, the probability of successful transmission when $\lambda(t_{icf})$ nodes are contending for the access is

$$p_{s,\lceil\lambda(t_{icf})\rceil} = \lceil\lambda(t_{icf})\rceil p_d (1-p_d)^{\lceil\lambda(t_{icf})\rceil - 1}. \qquad (3)$$

The reason for fixing $p_d = 1/\lambda(t_{icf})$ follows from the fact that (3) approaches maximum exactly with this value of p_d. Thus the expected number of unsuccessfully transmitted register packets is

$$W_{1n} = \begin{cases} V - t_{cp}/t_{sl}, & V > t_{cp}/t_{sl} \\ 0, & V < t_{cp}/t_{sl} \end{cases}, \tag{4}$$

where $V = \sum_{i=1}^{\lceil \lambda(t_{icf}) \rceil} p_{s,i}^{-1}$ We note that if all contending nodes would be able to receive information whether there was a successful transmission in a slot, then each remaining node could increase $p_d = 1/(\lceil \lambda(t_{icf} \rceil - s)$, where s is the number of successful transmissions in CP so far, which is equivalent to the number of slots in this CP.

B. Case 2 ($t_{icf} \lessapprox t_{cf}$)

In this case assuming that CH can capture one amongst i colliding packets, number of unsuccessful transmissions, W_{2c}, is defined exactly as in (2), changing all $\lambda(t_{icf})$ into $\lambda(t_{tot})$. In the non-capturing case analysis becomes much complicated due to three important phenomena. First, arriving traffic will consist of registration packets aggregated during t_{icf} and constantly arriving packets after each slot. Second, because CP length is fixed and small we cannot consider the system as in steady state during the contention. The average number of requests per slot becomes smaller after each successful transmission. For these reasons we omit analysis for this case here.

C. Probability of Scheduling Sensing to Non-existent Nodes

Knowing the average number of non successful nodes registering with a new cluster, for a particular transmission scheme, we can compute the probability that an MNG will schedule a measurement request to a node which is non existent in a cluster. It is defined as

$$P_s = 1 - \binom{N_C - \lceil W_{\{x\}} \rceil}{k_m} \binom{N_C}{k_m}^{-1}, \tag{5}$$

where $W_{\{x\}} \leq N_C$ is the average non successful number of nodes are where $x \in \{1c, 1n, 2c\}$. Now assuming that OSAN can accept only $P_s \leq P_{s,max}$, to obtain the average node number in the cluster, N_C, which results in such performance, we only need to find N_C by solving (5) over $P_{s,max}$.

D. Numerical Results

In Fig. 3 we plot the expected number of nodes unsuccessful in registering, for various channel access cases. We tried to choose most representative parameters for the OSAN operation, i.e. R, v, while plotting $W_{\{x\}}$. Obviously we observe that $W_{1c} < W_{1n}$ for high t_{icp} (in our case $t_{icp} \approx 6$ s). With the prolonged inter-scanning time we see that in the worst case maximal number of nodes that will not be able to register to the cluster is less than 6. This means that for the N_C we considered here only 2.4% of nodes will have to wait for the next CP phase. Using these values of P_s, we plot in Fig. 4 for different k_m values for case 1 multiaccess without capture. Interestingly, if the k_m is greater than W_{1n}, even for a substantial number of nodes within the cluster, when t_{icf} is long, probability of scheduling to a non registered node is moderate. This implies that there is a tradeoff between k_m and time between two scanning events, e.g. for fixed k_m increasing t_{icf} reduces QoD. We note that the stairs-like shape of the W_{1n} in Fig. 3 and plots in Fig. 4 are due to ceil function used in (3) and (5).

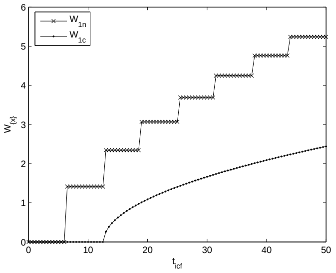

Fig. 3. Plots of the number of non successful nodes contending for the channel in the proposed protocol for case 1. N_C=250, R=500, t_{cp}=1 ms, t_{sl}=0.5 ms, v=0.5 m/s.

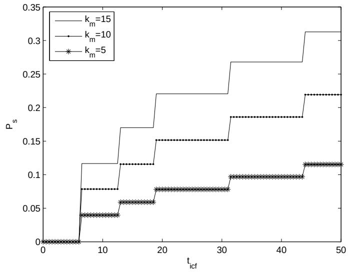

Fig. 4. Plots of probability of scheduling measurement to node non existent in the cluster for W_{1n} unsuccessfully registered nodes. N_C, R, t_{cp}, t_{sl}, and v are the same as in Fig. 3.

IV. CONCLUSIONS

In this paper we have proposed a simple architecture and protocol for spectrum management in OSAN. Our main concern here was to design a protocol for networks constructed with a two tier hierarchy. We have shown that not only the radio issues have a significant impact on the QoD, but also how the link layer protocol is designed. Specifically we provided detailed analysis of the impact of the mobility of nodes and in turn the contention on the LU detection quality (called in [7] as QoD).

However there are many issues in the protocol that need further analysis and study. First of all we assumed that all nodes within one cluster can reach CH and all CHs are within the radio range. Therefore we first have to perform the analysis for the reachability of nodes on the QoD. We also need to analyze the effects of transmission errors on the detection performance. Evaluation of total protocol time as well as synchronization issues will be also dealt in the future.

APPENDIX I
LU DUTY CYCLE DISTRIBUTION ANALYSIS

We have analyzed the measurements provided by the Dutch Radio Regulatory Body [1]. The set of measurements were performed in 10 different cities of the Netherlands. In one

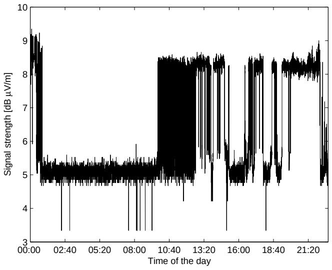

Fig. 5. An example of 24 hour measurement trace of LU activity for channel 445.6 Mhz taken in city of Heerhugowaard, the Netherlands. Measurement parameters: antenna height 30 m; inter-measurement interval 10 s; channel size 100 kHz; estimated noise level $\nu_m = 6\,\mathrm{dB}\mu\mathrm{V/m}$.

day electric field strength of frequency band 400-1000 MHz in 100 kHz bandwidth were gathered. We tried to find the distribution for the time period of ‘on’ and ‘off’ state of the selected channel, indicating the presence and absence of LU, respectively. We selected the range of 420-430 MHz assigned for mobile communication, e.g., public trunking, where we could easily see the transitions of LU activity from ‘on’ to ‘off’ state, and vice versa. We estimated the threshold for LU activity, $\nu_m = 6$ dBμ V/m. An example trace for channel 445.6 MHz is shown in Fig. 5.

Observing the characteristics of the LU activity on the selected channel we may notice that at some instances the channel is continuously ‘on’ or ‘off’ for a prolonged period sometimes exceeding a few hours. Therefore, we may see very less number of transitions from these long on-off time bursts and any reasonable statistical analysis is not possible for these longer periods. Thus we consider only the transitions that occur frequently in these measurements while the channel is not continuously in ‘on’ or ‘off’ state. We also found that, since the data collection is done at 10 s interval it is not possible to find a good match with any of the standard continuous distributions. We considered shorter ‘on’ and ‘off’ periods here for the analysis which was collected across all the 10 data sets for our study. We found that the channel is in ‘on’ state for an average of 72 s and in ‘off’ state for an average of 245 s. Interestingly, using histogram, we also found above 90% the ‘on’ periods were smaller than 61 s. Similarly, 76% of the ‘off’ periods were below 215 s. Since we see that a major chunk of the ‘on’ periods are concentrated within the first bin of the histogram, we treated it to be a *Bernoulli process*, with success probability of 0.9. Knowing the size of the bin (61 s) we consider all the ‘on’ periods to be equivalent to 61 s for simplicity. The channel remains in the ‘on’ state for approximately (1/0.9)61 s = 67.7 s. Similarly, once the channel has gone to the ‘off’ state, it remains ‘off’ for (1/0.76)215 s = 282.8 s.

APPENDIX II
CLUSTER CROSSING RATE

Assume uniformly distributed nodes over a circular area $\mathfrak{A}$ of radius R. At time t_0 all nodes are within $\mathfrak{A}$. We assume that at the time $t = t_0 + \Delta t$, where $\Delta t > 0$ each node has traveled with speed v a distance $d = vt$ along a straight line in a random direction. The proportion of nodes that have moved outside the service area, $\Omega = 1 - \frac{A}{\pi R^2}$, where

$$A = 2R^2 \cos^{-1}\left(\frac{d}{2R}\right) - \frac{1}{2}d\sqrt{4R^2 - d^2}$$

is the overlap area between two areas $\mathfrak{A}$ distanced d between their centers.

This observation is based on the fact that for a circular service area the number of nodes moved outside the area when they chose random directions is the same as when they all choose to move in the same direction. This statement can easily be verified using simulations. Mathematically we can substantiate this statement as well. With a circular service area, in all experiments when each node chooses a random direction to move, we may expect the same number of nodes to fall outside the service area. Therefore, there is no reason to assume that this number would be any different when this direction is the same for all nodes.

Assuming $z = \frac{d}{2R}$ we finally obtain

$$\Omega = 1 - \frac{2}{\pi}\left[\cos^{-1}(z) - z\sqrt{1 - z^2}\right].$$

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