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CORAL: Spectrum Aware Admission Policy in Cognitive Radio Mesh Networks

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***Abstract*—Spectrum sensing allows the cognitive radio (CR) devices to determine the presence of licensed users in the chosen spectrum band. Though several sensing methods based on energy detection and cyclostationary feature extraction have been proposed, they fail to account for the location-specific results, and provide no incentive for the node to perform sensing at the cost of its own data throughput. In this work, a node admission policy called CORAL is proposed for CR wireless mesh networks that ranks candidate joining mesh clients (MCs) based on their distinct contributions towards the spectrum sensing coverage area. Moreover, CORAL incorporates different traffic classes, and attempts to keep the higher ranked MCs affiliated to the mesh cluster for longer durations of time. Simulation results reveal improved throughput and enhanced PU protection in the area, in which the licensed and CR users co-exist.**

I. INTRODUCTION

Wireless mesh networks (WMNs) provide Internet connectivity to the end users or mesh clients (MCs) that associate with the mesh routers (MRs), by carrying their traffic over the multihop packet forwarding backbone formed by the MRs [1]. One or more of the MCs join an MR, thereby forming a *mesh cluster*, and all uplink traffic is routed from the MCs to the MR of the cluster in which it belongs, and then forwarded over several intermediate MRs till it reaches the gateway. With the rapid growth of wireless mesh network implementations in the unlicensed $2.4\,\mathrm{GHz}$ ISM band, and increasing use of high bandwidth multimedia content, the problem of spectrum scarcity is a critical concern [5]. The emerging field of cognitive radio (CR) networks attempts to alleviate the problem of spectrum shortage in the ISM band by opportunistically transmitting on other vacant portions of the spectrum, such as frequencies licensed for television broadcast and public services [2]. In this paper, we explore how WMNs use these frequencies without interfering with the licensed or primary users (PUs) that have access priority, by a novel spectrum-aware admission policy.

Spectrum sensing is one the critical tasks in a CR network, in which the presence of the PU is detected before transmitting in the licensed band. In a WMN, the associated MCs undertake spectrum sensing, and report their readings to the MR. As each MR serves several MCs, the former obtains multiple sets of readings that help in improving accuracy, eliminate outliers, and present a view of the network environment that is beyond

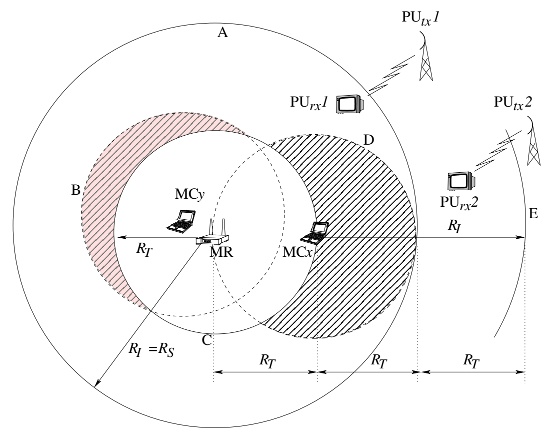

Fig. 1. The transmission and interference ranges in a CR WMN cluster.

the sensing range of the MR alone. Consider Figure 1, in which the MR has two MCs, x and y, respectively within its transmission range R_T. The interference range is $R_I = 2 \cdot R_T$, without loss of generality, and the spectrum sensing range (R_S) is equal to the interference range (R_I). While the MR can detect the presence of a PU transmitter within its sensing range (circle A), it is unable to detect the presence of other distant PU transmitters 1 and 2, unless other MCs such as x report their presence to the MR. Moreover, the PU receiver cannot be easily detected even if it lies within the sensing range of the MR. Thus, the MR continuously interferes with the PU receiver as it can neither detect the latter's presence, nor the transmitting senders in this scenario [10].

There are several concerns in the model of relying completely on a randomly selected set of MCs for spectrum sensing information. Firstly, if the MCs do not cover the entire interference range of the MR, then it is possible that even with multiple readings, there is an error in estimating the presence of the PUs. Secondly, assuming single-transceiver nodes, the MCs are unable to transmit useful data to the MR when they are engaged in sensing the spectrum, which leads to reduced throughput. Thus, the MC must be provided an incentive to continue sensing the spectrum information though it has no direct gain resulting from this action. We address the above challenges through our proposed COgnitive Radio Admission

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controL (CORAL) for WMNs.

CORAL classifies a given MC into one of several possible *ranks* based on the proportion of the distinct area covered by it for spectrum sensing. Thus, with respect to the central MR (Figure 1), the concentric circles A and C represent the interference and transmission coverage regions, and have radii R_I and R_T respectively. The partially shaded circles B and D give the transmission regions of MCs x and y, respectively. The circles centered at the MC location, and having a radius of R_I, give the spectrum sensing area that the MCs may cover. For MC x this region is represented by circle E (shown partially), and is the area that the MC monitors for informing its MR of possible PU activity. As new MCs join the network, the *admission policy* attempts to maximize the spectrum coverage region by ranking higher the nodes that make the maximum distinct contribution towards the spatial extent of spectrum sensing knowledge. In this example, CORAL ranks MC x higher than MC y, and consequently, has a higher preference for keeping the former node associated with the mesh cluster. In our work, we combine the optimal spectrum sensing and transmission duration proposed in [12] with the data rate at which each user is allowed to transmit, based on its traffic requirement. In return, the higher ranked MCs enjoy a longer duration of association time with the MR, with the guarantee of bandwidth availability for supporting its traffic requirement. Over time, the MR performs *node management* through which it modifies existing traffic class assignments based on changes in the topology and may de-associate MCs having a lower rank that consume bandwidth without providing useful spectrum information.

We consider 4 different traffic classes that may be supported by the MR. Each of these classes enjoys a different available bandwidth by uniquely associated the tuple $<AIFSD_\psi, CW_\psi^{max}, CW_\psi^{min}>$ for traffic class ψ, similar to the QoS provided by 802.11e [7]. Here, $AIFSD$ gives the carrier sensing time, CW^{min} and CW^{max} are the minimum and maximum value of the contention window, respectively. Though each MC may have its own bandwidth requirement, the MR allocates it, after admission to the mesh cluster, one of these 4 classes such that the resulting bandwidth is equal to or greater than the needs of the MC. There have been several recent works focusing on WMNs enabled with CR ability [13] [8]. A spectrum sensing and sharing scheme was proposed in [4] in which different MCs send their local energy readings for a channel to the MR, which used an LPP formulation to extract specific frequencies used by the PUs. However, this work assumed that the effect of every PU transmitter affected each MC. A graph theoretical approach is proposed in [11] while an experimental design for a CR WMN is given in [3]. The effect on the WMN due to an external PU activity is presented in [9].

The rest of this paper is organized as follows. In Section II, we describe our proposed admission policy in detail. The node management policy is given in Section III. We undertake a thorough performance evaluation in Section IV, and finally, Section V concludes our work.

II. CORAL: Admission Policy for CR Mesh Networks

The CORAL admission policy is composed of a series of message exchanges (`PROBE, RESPONSE, REQUEST, CONFIRM`) between the MR and the candidate MC x that wishes to join the mesh cluster, each message carrying information that allows these network entities to assess, from their own perspective, the value of a possible association.

The `PROBE` message is broadcast by a candidate MC x advertising its intention of joining a mesh cluster. Both MRs j and k that receive this packet, calculate the rank ($r_{x,j}$ and $r_{x,k}$) for the MC x based on the location information and the distinct spectrum-coverage region that it can potentially monitor, through the procedure `Rank()`.

The `RESPONSE` messages are sent by the MRs containing their respective ranks for the candidate MC x, and also the residual bandwidth available for their mesh clusters. If the MC can indeed be accommodated, the MR also assigns it a traffic class B_x^{class} that meets the bandwidth requirement of the MC. The MC chooses, through the procedure `Join()`, the MRs (here, MR j) that allots it a higher rank, and tie-breaks are broken by the residual capacity of the MR.

The `REQUEST` message is sent to the chosen MR, and the latter must ensure that the bandwidth availability for the existing higher ranked MCs are not affected because of the new node joining the cluster. The procedure `Maintain()` checks this condition, and may involve de-associating certain lower ranked MCs to ensure bandwidth availability to the others with higher ranks. Finally the `CONFIRM` message concludes the admission round, and the MC is completely assimilated in the mesh cluster. Next, we describe the above operation in detail by detailing the constituent procedures of our admission policy, namely `Rank()`, `Join()` and `Setup()`.

A. Procedure: Rank()

Considering the MR in Figure 1, the circular region represented by A is the sensing (also interference) range, and can be completely monitored by the MR for PU transmitters. However, the additional spectrum usage information collected by the MCs in the region between the circles E and A (*shadow region* for MR) may reveal the presence of possible PU transmitters. From geometrical conditions, the maximum distinct coverage area $A_{x,j}$ in the shadow region that may be contributed by an MC, say x, associated with the MR j is:

$$A_{x,j} = 2R_I^2 cos^{-1}\left\{\frac{D_{x,j}}{2R_I}\right\} - \frac{(s-2R_I)}{2}\sqrt{s(s-2D_{x,j})}, \tag{1}$$

where $s = (D_{x,j} + 2R_I)$ and $D_{x,j}$ is the distance between the MC x and MR j. R_I is the interference range. Now, for obtaining the upper bound A^{max} on the maximum distinct coverage, the MC is located just at the maximum transmission range of the MR, i.e., $D_{x,j} = R_T$. Substituting this in equation (2),

$$A_{x,j} = 2R_I^2 cos^{-1}\left\{\frac{R_T}{2R_I}\right\} - \frac{R_T}{2}\sqrt{4R_I^2 - R_T^2}, \tag{2}$$

Using $R_I = 2 \cdot R_T$, we get the simplification,

$$A^{max} = 2.42 R_I^2 \quad (3)$$

The observed distinct overlap $A^{obs}_{x,j}$ is generally less than the maximum value $A_{x,j}$, and is dependent on the individual coverage areas contributed by the existing MCs of the cluster. Thus, taking the complement of the intersecting coverage regions among all the existing MCs,

$$A^{obs}_{x,j} = A_{x,j} - A_{x,j} \bigcap A_{i,j} \, \forall i \in N_j^{MC}, \quad (4)$$

where N_j^{MC} is the set of MCs currently associated with the MR j.

Ranks are assigned to candidate MCs by comparing $A^{obs}_{x,j}$ with the upper bound A^{max}. Specifically, the assigned rank $r_{x,j}$ is an integral value in the range $[0, r_{max} - 1]$, and calculated as:

$$r_{x,j} = \left\lfloor \frac{A^{obs}_{x,j}}{A^{max}} \right\rfloor \times r_{max} \quad (5)$$

The algorithm that jointly takes into account the traffic requirement of an MC and assigns it a rank is formally described as follows:

```
PROCEDURE:Rank()
Input: N_j^{MC}, L_x, B_x^{req}
B_j = C − Σ_{∀i∈N_j^{MC}} B_i^{MC}
if B_x^{req} ≤ C then
    r_{x,j}=CALCULATE(L_x, N_j^{MC})
    N_j^B = φ
    r_cur = 0
    while (1/η) · B_x^{req} > B_j  & do
        r_cur = 0
        for (i ∈ N_j^{MC}  &  r_{i,j} == r_cur) do
            N_j^B = N_j^B ⋃ i
            B_j = B_j + B_i^{MC}
            if |N_j^B| == |N_j^{MC}| then
                Exit
            end
        end
        r_cur = r_cur + 1
        if r_{x,j} == r_cur then
            Exit
        end
    end
    SEND RESPONSE (r_{x,j}, B_j)
end
```

The `Rank()` procedure takes as inputs the information (currently observed bandwidth and coverage) about each of the MCs in N_j^{MC} currently associated with MR j. I also requires the location (L_x) and the requested bandwidth (B_x^{req}) by the candidate MC x.

First the residual capacity of the MR is obtained by the difference of the total capacity C and the bandwidth B_i^{MC} currently used by the MCs $i \in N_j^{MC}$ in the cluster. If the bandwidth request is feasible, i.e., within the limits of C, then the procedure first identifies the rank that must be assigned to the candidate MC through the CALCULATE operation, based on equation (5). This operation takes in as inputs the location of the MC x and the coverage information for the existing cluster nodes N_j^{MC}. Next, the *blacklist* N_j^B is created, which is composed of nodes that may need to be de-associated to make the requisite bandwidth available for the MC x. If the residual bandwidth is enough to meet the requirements of MC x, then no change is necessary at the MR. Otherwise, the initially empty *blacklist* is populated by adding the existing MCs of the cluster to it. Beginning from the lowest rank ($r_{cur} = 0$), and in the ascending order of ranks upto the rank assigned to the candidate MC x, MCs may be iteratively placed in the *blacklist* to assess how much bandwidth can be re-gained by the MR. The underlying aim of this step is estimating how many, if at all, lower ranked MCs need to be de-associated for assigning the requisite bandwidth to the candidate MC x. Thus, the lower ranked MCs are successively placed in the *blacklist*, till the limiting rank of $r_{x,j}$ is reached, or all the MCs in the MR are considered. Note that the MCs in the *blacklist* are not directly de-associated at this stage.

The bandwidth that is actually assigned to the MC x is greater by a factor of $\eta < 1$ than the requested bandwidth B_x^{req}. This is because we also incorporate the loss of bandwidth during operation of the network due to the spectrum sensing function. We integrate the sensing and transmission time optimization given a target probability of missed detection of a PU (P_f), i.e., the probability stating the spectrum to be available when indeed there is an ongoing PU activity. Based on the bandwidth of the channel (W), the external signal to noise ratio (γ), and the known statistical probabilities of the on period (P_{on}) and the off period (P_{off}) of the PUs on the channel, a framework to calculate this time is given in [12]:

$$t_x^s = \frac{1}{W \cdot \gamma^2}[Q^{-1}(P_f) + (\gamma + 1)Q^{-1}(\frac{P_{off}P_f}{P_{on}})]^2 \quad (6)$$

Equation (6) gives the sensing time t_x^s at MC x that minimizes the probability of missed primary user detection P_f, and Q is the standard Q function. Thus, for a target transmission duration t_x^t, the bandwidth B_x^{class} assigned to the candidate MC x must satisfy the following relationship with the requested value B_x^{req}:

$$\frac{t_x^t \times B_x^{class}}{t_x^s + t_x^t} \geq B_x^{req} \quad (7)$$

The scaling factor η can be obtained as $\frac{t_x^t}{t_x^s + t_x^t}$, and this must be considered while calculating how much bandwidth is actually reclaimed to accommodate MC x during the process of *blacklist* creation .

B. *Procedure: Join()*

Once the MC sends out the PROBE it starts a countdown timer for a small duration t_{delta} and waits for possible reception of multiple RESPONSE messages from the MRs. Let the set of MRs responding to MC x be denoted by N_x^{MR}. The procedure through which MC x can select on of these MRs is as follows:

```
PROCEDURE:Join
Input: r_{x,i}, B_i ∀i ∈ N_x^{MR}
FIND MR_select = q | r_{x,q} = max {r_{x,i} ∀i ∈ N_x^{MR}}
if ∃r_{x,i} ≥ r_{x,q}  &  q ≠ i then
    if B_i > B_q then
        MR_select = i
    end
end
SEND REQUEST (MR_select)
```

In Algorithm 2, the outer loop cycles through all the MRs in the set N_x^{MR}, and considers, in the order of the received RESPONSE messages, the one with which assigns MC x the highest rank. In case of a tie, the residual bandwidth advertised by the MR is used as a deciding metric. The greater the value of B_i, more the number of MCs that can be accommodated by the MR, and this is an indication that the latter is unlikely to begin de-associating MCs in the near future owing to bandwidth limitations. As we describe in Section III, the MRs periodically perform maintenance functions, which may cause lower ranked MCs to be preferentially de-associated to make available bandwidth of those with higher ranks. Thus, a higher value of the residual bandwidth is an indication that the MC may remain associated in the cluster for a larger duration. The chosen MR (MR_{select}) is then informed via the REQUEST message.

C. Procedure: Setup()

This procedure aims to accommodate the new MC without affecting the bandwidth allotment of the higher ranked MCs. In this stage, one or more existing MCs of the cluster may be de-associated. The MR also performs the necessary background tasks, such as informing the candidate MC of the spectrum choice, link and physical layer configuration parameters, necessary for establishing the environment for the CR operation.

```
PROCEDURE:Setup()
Input: N_j^B, N_j^{MC}
Sec_init = 1
Sec_cur = Sec_init
while N_j^B ≠ φ do
    FIND y | r_{y,j} = r_{i,j}, where i ∈ N_j^B  &  L_y ∈ Sec_cur
    N_j^B = N_j^B / {y}
    REMOVE (y)
    Sec_cur = Sec_cur + ⌈Sec_max / |N_j^B|⌉
    if Sec_cur > Sec_max then
        Sec_init = Sec_init + 1
        Sec_cur = Sec_init
    end
end
SEND CONFIRM
```

If the residual bandwidth B_j for MR j is greater than the bandwidth requested B_x^{req} by the newly joining MC x, then it is simply allocated the traffic class ψ identified by the tuple <$AIFSD_\psi, CW_\psi^{max}, CW_\psi^{min}$> that provides a bandwidth (B_x^{class}) greater or equal to the B_x^{req}. In this case the *blacklist* $N_j^B = \phi$ (Section II-A), and the outer **while** condition evaluates to *true* and no further adjustment is needed. Consequently, the CONFIRM message is directly sent. As opposed to this, if $B_j < B_x^{req} \cdot \frac{1}{\eta}$, then one or more MCs belonging to a lower rank must be de-associated to free up the requisite bandwidth.

Instead of using the *blacklist* directly to de-associate MCs, CORAL attempts to choose them uniformly around the MR, while maintaining the same order of preference of the ranks used to create the *blacklist*. The transmission region of the MR is divided into sectors, with progressively increasing identifying numbers in the counter-clockwise direction. The FIND operation identifies an MC, say y, belonging to the same rank as the node selected in the *blacklist*, but in the current sector Sec_{cur}. The pointer Sec_{cur} is incremented by a constant value $\lceil \frac{Sec_{max}}{|N_j^B|} \rceil$ so that the next MC chosen for de-association is located at a proportional distance (in a radial sense) away from the previously chosen one. As an example, if the maximum number of sectors $Sec_{max} = 12$ and the *blacklist* is of size 7, then sectors $1, 3, 5, 7, \ldots$ are chosen. If $|N_j^B| > Sec_{max}$ then it is possible that for all subsequent turns that complete one full rotation, the same sectors are repeatedly chosen. To avoid this condition, if $|N_j^B| > Sec_{max}$, the starting sector Sec_{init} is incremented by 1 for the next round, once the current cycle is completed. Hence, the 7^{th} MC is chosen from sector 2. The REMOVE operation informs the MC that of the de-association, and it may send out PROBE message if it wishes to find another MR for continued operation.

III. Node Management in CORAL

The bandwidth allocation to the candidate MC occurs by choosing a traffic class that has an expected bandwidth greater or equal to the value requested by the MC. This approach was also explored in [7], and it was demonstrated to get higher performance compared to an approach with fixed priorities for traffic class (e.g. 802.11e EDCA scheme). However, owing to node leave and join events, or imprecise calculation of the expected value, the actual bandwidth available to the MC may fall short of its requested value, as is seen in [7]. Thus, periodically, CORAL evaluates the bandwidth for each MC and re-adjusts its traffic class based on the current situation.

The steps in node management follow the procedure Management() as described below:

```
PROCEDURE:Management()
Input: B_i^{req} ∀i ∈ N_j^{MC}
r_cur = r_max − 1
while r_cur ≥ 0 do
    for ∀i ∈ N_j^{MC}  &  r_{y,j} == r_cur do
        if B_i^{cur} < B_i^{req} then
            FIND Class ψ | B^ψ > B_i^{class}
            B_i^{class} = B^ψ
            CREATE N_j^B
        end
        PROCEDURE: Setup(N_j^B, N_j^{MC})
    end
end
```

The above procedure checks if a given MC i, in the descending order of the ranks, i.e., from rank $r_{max} - 1$ to

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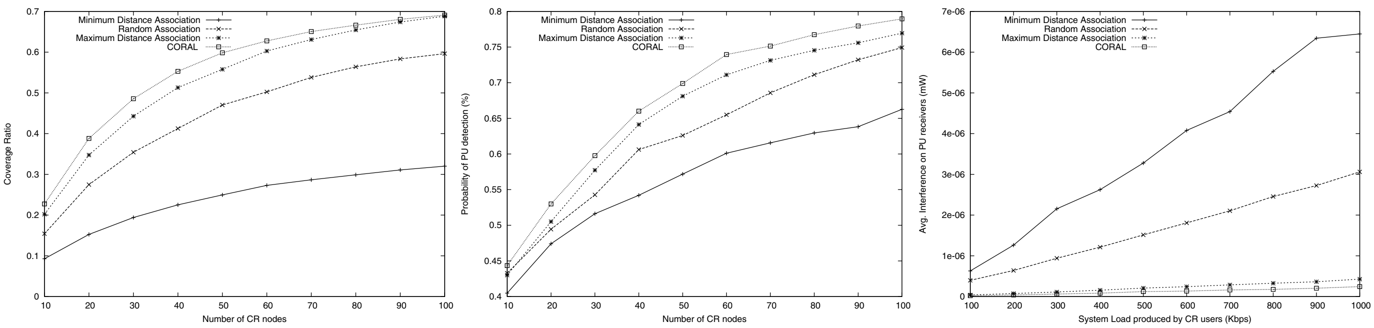


(a) (b) (c)

Fig. 2. The coverage ratio is given in (a). The probability of correct PU detection is given in (b), and the average interference at the PU receivers with varying system load is shown in (c), respectively.

rank 0, has a current observed bandwidth B_i^{cur} less than its requested share at the time of joining the mesh cluster. If so, it upgardes the MC to a higher traffic class ψ resulting in $B^{\psi} > B_i^{class}$. If the MR can support this higher bandwidth allotment, then there is no other change to the cluster. If this is not true, then the lower ranked MCs may be de-associated by running the previously described `Setup()` procedure. The `CREATE` operation allows the construction of a new *blacklist* as described in Section II-A, and not repeated here for the purpose of brevity. This allows dynamic checking of the traffic classes and observed bandwidth utilization even, when there are no new node join events. The order of checking from the higher rank downwards ensures that MCs with greater distinct spectrum coverage are assured of their bandwidth requirement continuously.

IV. Performance Evaluation

In this section, we study the behavior of CORAL by investigating the (i) effect of interference caused by the mesh network on the PU receivers, and (ii) quality of service support for the MCs. We use the ns-2 simulator with the additional CR module developed by us for this experimental evaluation [6].We consider a topology composed of 9 MRs arranged in a grid with each being associated with a variable number of MCs. The transmission range is $250\,\mathrm{m}$ for each node in the network. A total of 20 PU transceiver pairs are distributed randomly in the study area, with three licensed channels. For the PU, the "$P_{on} = \frac{1}{alpha} = 1$" seconds, while the "$P_{off} = \frac{1}{\beta}$" is assigned a value $\{1, \frac{1}{5}, \frac{1}{10}\}$, for the channels $\{1, 2, 3\}$, respectively.

A. Effect of interference caused by the WMN to the PUs

In this study, we compare CORAL with three different admission policies: (i) *maximum distance*, where the MC furthest away from the MR is ranked highest, (ii) *minimum distance*, where the closest MC is preferred the most, and (iii) *random* where no given MC is preferred over the other.

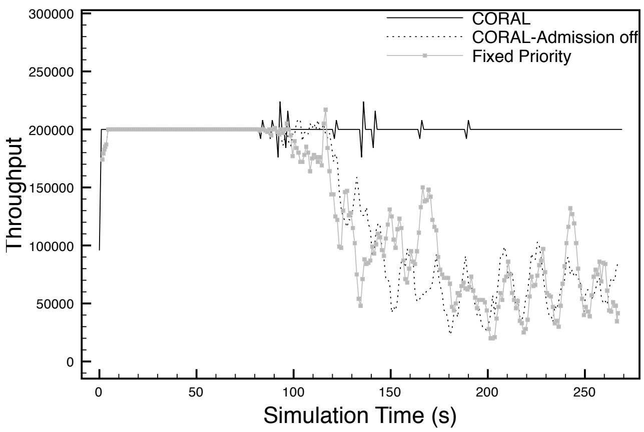
For the subsequent discussion, we define the *coverage ratio* as the ratio of the actual region covered by the MCs associated with the given MR, and the region between the sensing (or interference) ranges of the MR and the MCs.

From Figure 2(a), we observe that the coverage ratio is the maximum for CORAL for increasing number of MCs, which implies that greatest extent of the area that may have PU receivers is covered. Moreover, while the maximum distance and CORAL reach the same coverage ratio for very high number of MCs, the minimum distance and random scheme never converge with CORAL even asymptotically. Classically, MR-MC associations are based on higher signal strength (minimum distance) or on a first-come basis (random). It is clear that neither of these admission policies are good for a CR environment, and CORAL performs consistently better even for lower number of MCs.

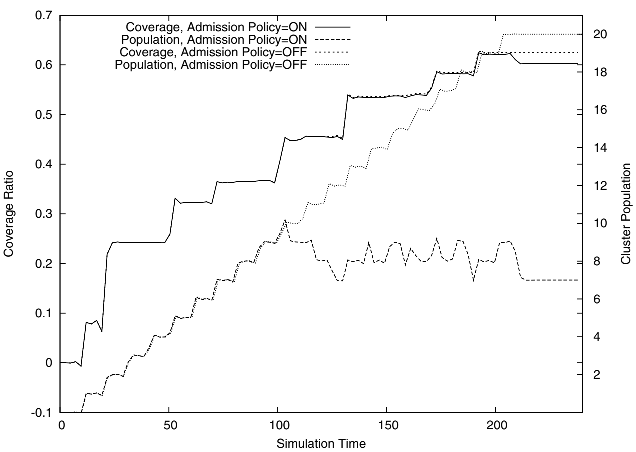
Next, we compare the probability of PU transmitter detection owing to the increased reach of the spectrum sensing function in our approach (Figure 2(b)). As the density of MCs increases, the probability of detection also improves with CORAL continuously performing 5% better than the maximum distance, and 15% better than minimum distance association, respectively. Figure 2(c) measures the direct result of interference to the PU receivers for increasing system load (hence, transmission rate). In this case, CORAL shows a significant improvement over both the minimum and random associations, closely followed by the maximum distance scheme.

B. Quality of service support for the MCs

In this study, we show the throughput variation for new MCs that attempt to join a given mesh cluster every $10\,\mathrm{s}$. The requested bandwidth, in terms of throughput, is considered to be constant at $200\,\mathrm{Kbps}$ for each MC in Figure 3(a). We observe that the new users are added on without any de-associations till around $90\,\mathrm{s}$ in CORAL. Subsequently, CORAL performs at the desired bandwidth level by intelligently choosing which MCs to admit in the cluster through its admission policy. The constant line shows that the bandwidth requirement of each MC is satisfied. By switching the admission policy *off* (i.e. CORAL-Admission off, obtained by admitting every node that wishes to join) , we observe that the resulting throughput undergoes wider fluctuations, in which MCs enter



(a)



(b)

Fig. 3. Meeting bandwidth requests of incoming MCs for 200 Kbps (a), the relationship between coverage ratio and number of MCs in a cluster (b), respectively.

the cluster, and then within a very short duration, they get de-associated. This is because CORAL manages to move the MCs to different traffic classes, other than the one assigned during joining, during the management phase (Section III) and prunes out the lower ranked ones. When there is no priority, the MCs continuously enter the cluster, contributing majorly to congestion, and the resulting throughput falls rapidly.

Figure 3(b) shows how CORAL manages to maintain the same coverage ratio as the random admission policy but by requiring fewer number of MCs. However, unlike the random case in which the bandwidth requirement was never met after a certain density of MRs, CORAL ensures that for each of the admitted MCs (around $7-9$ in a cluster), the requested bandwidth is continuously delivered. The fluctuations are as the result of the bandwidth estimation action by CORAL during node admission and node management, respectively.

V. Conclusions

Our proposed approach CORAL presents a novel admission policy for CR networks in which the location of the candidate MC with respect to the MR is considered as an important metric. The unique spectrum sensing coverage region that each MC contributes determines its rank, and consequently, the duration over which it enjoys uninterrupted association with the MR. The different bandwidth requirements of the MCs are accounted by considering traffic classes, and a best effort is made for accommodating the quality of service requirement of the MCs. Results reveal increased protection to the PU receivers, which go otherwise undetected. We plan to extend our approach further by integrating accuracy of the sensing result in determining ranks of the MCs, and investigating the costs associated with cooperative sensing.

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