Radio Co-location Aware Channel Assignments for Interference Mitigation in Wireless Mesh Networks

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Abstract—Designing high performance channel assignment schemes to harness the potential of multi-radio multi-channel deployments in wireless mesh networks (WMNs) is an active research domain. A pragmatic channel assignment approach strives to maximize network capacity by restraining the endemic interference and mitigating its adverse impact on network performance metrics. Interference prevalent in WMNs is multi-dimensional, radio co-location interference being a crucial aspect that is seldom addressed in research endeavors. In this effort we propose a set of intelligent channel assignment algorithms, which focus primarily on alleviating it. These graph theoretic schemes are structurally inspired by the spatio-statistical characteristics of interference. We present the theoretical design foundations for each of the proposed algorithms, and demonstrate their potential to significantly enhance network capacity in comparison to some existing well-known schemes. We also demonstrate the adverse impact of radio co-location interference on the network, and the efficacy of the proposed schemes in successfully mitigating it. The experimental results validate the proposed theoretical notions were obtained by running an exhaustive set of NS-3 simulations on an IEEE 802.11 environment.

I. INTRODUCTION

Wireless Mesh Networks (WMNs) exhibit immense potential to pervade the domain of enterprise and social network deployments, promising extensive high-speed connectivity with significantly enhanced bandwidths. Low-cost availability of the commodity IEEE 802.11 hardware coupled with ease of deployment and effortless scalability have sparked a great interest in WMN technology. They are a precursor to the next-generation of wireless communication systems which envision an integration of cellular mobile technologies viz. 3G, 4G/LTE, 5G etc. with wireless local area network (WLAN) technologies based on IEEE 802.11 standard onto a single platform to achieve seamless network-convergence [1]. The WMN technology is beginning to find its presence in a plethora of application scenarios such as campus networks, backhaul networks of mobile communication frameworks, broadband Internet access, disaster-mitigation and public-safety networks etc., to name a few. The benefits of increased throughput, enhanced connectivity and reduced latency promised by a multi-radio multi-channel (MRMC) WMN are predicated upon the feature of reduced interference that is not a characteristic of the network itself, but instead, of the channel assignment (CA) scheme. Minimizing the interference in a WMN is thus a fundamental system design and operational objective and the most crucial aspect of achieving this goal is an optimum and feasible CA to the radios in the WMN. A prudent CA will reign in the interference and its detrimental effects and in turn enhance the capacity of the mesh network and improve overall network performance.

II. MOTIVATION AND RELATED RESEARCH WORK

In a recent research study [2], we have focused on the concept of radio co-location interference (RCI) [3] and its detrimental impact on the performance of a WMN, a problem domain that has so far remained largely unaddressed. RCI is caused and experienced by spatially co-located radios at a node, that have been allocated identical channels to communicate on. We proposed an Enhanced Multi-Radio Multi-Channel Conflict Graph (E-MMCG) model, which enables a CA algorithm to mitigate the adverse impact of RCI and substantially enhances the performance of the deployed CA. The E-MMCG model takes into account the interference scenarios spawned and experienced by the spatially co-located radios (SCRs) at a node in the WMN, and adequately represents them in its conflict graph (CG). The E-MMCG model accomplishes this by adding an edge between two vertices of the conflict graph if and only if, the respective wireless links in the WMN emanate from or terminate at the same node, and have been assigned an identical channel. The E-MMCG thus generated is a comprehensive representation of all possible conflict links in a WMN, including the RCI scenarios, and serves as an ideal input to CA schemes.

The CA problem is an NP-Hard problem [4], and substantial research effort has been focused towards finding efficient CAs for WMNs, yet to the best of our knowledge, no proposed CA scheme incorporates RCI alleviation as a design objective. The CA approaches can be broadly classified into three categories, viz. static, dynamic and hybrid. A static scheme mandates a fixed radio-channel mapping throughout the session for which the network is operational. Dynamic CA features updating of the CA continuously, based on the analysis of network metrics, for better efficiency and throughput. They can be both centralized and distributed. Hybrid CAs employ characteristics of both static and dynamic CA schemes, efficiently assigning a fixed CA to some radio interfaces and a dynamic CA to others. Several CA schemes have been proposed in earlier research studies [5], of which we cite a few. A centralized Breadth First Traversal (BFT) approach BFS-CA, has been suggested in [6] where channels are assigned to nodes, after performing a BFT with the Gateway node as the reference. A static maximum clique based algorithm is discussed in [7]. In [8] authors...
proposed MaIS-CA, a Maximum Independent Set (MIS) based high performance CA, where MIS of the conflict graph (CG) is determined iteratively, and channels are assigned to the nodes of the MIS in each step. A centralized static CA scheme is proposed in [9], where nodes of the CG are assigned channels so that the Total Interference Degree (TID) decreases, resulting in an efficient CA. TID is a theoretical estimate which gives a measure of the intensity of the interference prevalent in a WMN. It is the sum of the individual conflict numbers of all links, where conflict number of a link represents the total number of potential link conflicts experienced by that particular link in a WMN.

However, the absence of RCI mitigation as a crucial design consideration is bound to hamper the efficiency of a CA, as it does nothing to restrain the RCI. Thus, it is imperative that CA algorithms be Radio Co-location Aware or RCA i.e., consider RCI as an impeding factor while assigning channels to the radios in a WMN. In current research effort, we propose two RCA CA algorithms. The schemes are static, as the primary bottlenecks in dynamic and hybrid CAs are the channel switching delays, and the need of a mechanism for co-ordination between nodes to ensure that they are on the same channel when they intend to communicate [10].

III. Problem Definition

Let $G = (V, E)$ represent an arbitrary MRMC WMN comprising of $n$ nodes, where $V$ denotes the set of all nodes in the WMN and $E$ denotes the set of wireless links between nodes which lie within each other’s transmission range. Each node $i$ is equipped with a random number of identical radios $R_i$, and is assigned a list of channels $C_i$. The number of available channels is greater than the maximum number of radios installed on any node in the WMN. For the WMN described above, we propose RCA CA schemes, which allocate channels to every node $i$ in the WMN i.e., $C_i = C_{RCA}(G)$, so as to efficiently mitigate the detrimental impact of RCI.

IV. Radio Co-location Aware Channel Assignments

We now present the two RCA CA algorithms. The proposed algorithms benefit from the following design considerations.

1) Enhanced Conflict Graph Model: RCA CA algorithms ought to employ the use of the E-MMCG model [2] to generate the E-MMCG of a WMN, which usually serves as the input to CA schemes. This broad-based model accounts for the prevalent RCI and adequately represents it in the CG of the WMN.

2) Efficient Radio Co-location Optimization: This is the signature functionality of the RCA CA algorithms. It ensures that spatially co-located radios are not allocated identical channels to communicate on. In addition, it may also serve as an optimization step by restraining the detrimental effect of interference over network performance.

3) Spatio-Statistical Interference Alleviation: A static CA, due to its inherent rigidity of radio-channel mapping, can only address the spatio-statistical aspects of the three dimensional interference-mitigation problem, the third dimension being the temporal or dynamic characteristics. A scheme primarily catering to the spatial features of interference will effect a CA in which links on identical or overlapping channels are efficiently interspersed with links operating on respective orthogonal channels. An intelligent spatio-statistical scheme, in addition to spatial prudence, will strive to evenly distribute the available channels among the radios, thereby facilitating an efficient CA with enhanced fairness.

4) Network Topology Preservation: The apparent trade-off between ensuring connectivity at the cost of increased interference, holds its relevance in reduced propagation delays between end-nodes, and seamless uninterrupted connectivity to the end-user. Further, a CA approach should not alter the original WMN topology to ensure the functional independence of physical spatial design of the WMN from the channel allocation exercise. We opine that the WMN topology ought to be preserved after a CA deployment. Thus the proposed algorithms are graph theoretic approaches which restrain the RCI by leveraging the twin interference mitigation features, viz the E-MMCG model and Radio Co-location Optimization and also incorporate spatial and statistical dimensions of the prevalent interference in their structural design, to fashion efficient high-performance RCA CAs.

Notations common to both the algorithms are, $G$: The WMN graph, $G_r$: E-MMCG of the WMN graph, $CS$: The set of $M$ available channels, $Adj_i$: The set of nodes adjacent to node $i$ in $G$, $Ch_i$: The list of channels allocated to the radios of node $i$ in $G$; It may have duplicate elements, which will reflect the impact of RCI at node $i$. $TID(G)$: The function which computes the total interference degree (TID) i.e., the estimate of prevalent interference in a WMN.

A. RCA Optimized Independent Set (OIS) CA

This graph-theoretic RCA CA scheme appeals to the statistical aspects of channel assignment. We contend that, given two CA schemes with similar spatial patterns, the one with a more proportionate distribution of available channels among the radios of the WMN will perform better. We will validate this argument with TID estimates, and further through rigorous simulations.

The method of assigning channels to radios based on the Maximal Independent Set or MIS approach finds numerous references in the research literature [11] [8]. However, we contend that the MIS approach is not statistically pragmatic with respect to the channel allocation exercise, and an IS approach stands to fare better. For example, the MaIS scheme elucidated in [3] suggests that in each iteration, an MIS of the updated CG be determined, all vertex elements of the MIS be assigned a common channel and then removed from the CG. By its very definition, an MIS can not add even a single vertex to its element set lest it violate its independence. Further, an MIS may or may not be a maximum IS. Yet,
we can infer that as the cardinality of the vertex set of the CG decreases in subsequent iterations, the MaIS scheme is disposed to generate MISs with decreasing cardinals as well. Now, since a channel is assigned to all the vertices in an MIS in each step, the distribution of channels among radios is bound to be uneven. To validate our argument, we employ MaIS algorithm to generate MISs for WMN grids of size \((N \times N)\), where \(N \in \{5,...,9\}\). Every node is equipped with two identical radios and there are three orthogonal channels \(C_1, C_2 \& C_3\), available to be assigned to a radio. \(C_1\) is the default channel on which all radios were initially operating to generate the E-MMCG. We ascertain the statistical evenness of a CA for a WMN grid by determining the ratio of the number of radios operating on each channel denoted by \(R_{C_1}, R_{C_2} \& R_{C_3}\), normalized by the smallest value observed for a channel. The results are illustrated in Table I. It can be discerned that there is a skewed distribution of channels among the radios. The number of radios which are allocated \(C_3\) is always at least 50\% more than those on \(C_1\), which is the default channel and is consistently under utilized in the final CA. The difference between \(R_{C_2}\) and \(R_{C_1}\) is also never below 33\%, highlighting a statistically uneven allotment of channels to radios.

### Table I: Equitable channel distribution, RCA OIS-CA vs MaIS-CA

| Grid Size | Num of Radios | \(R_{C_1}: R_{C_2}: R_{C_3}\) | MaIS | RCA OIS |
|-----------|---------------|-----------------|------|---------|
| 5\times5  | 50            | 1.00 : 1.63 : 1.94 | 1.00 : 1.06 : 1.06 |       |
| 6\times6  | 72            | 1.00 : 1.33 : 1.66 | 1.00 : 1.09 : 1.33 |       |
| 7\times7  | 98            | 1.00 : 1.56 : 1.69 | 1.00 : 1.00 : 1.16 |       |
| 8\times8  | 128           | 1.00 : 1.48 : 1.64 | 1.00 : 1.00 : 1.28 |       |
| 9\times9  | 162           | 1.00 : 1.58 : 1.57 | 1.08 : 1.00 : 1.29 |       |

We now present \textbf{RCA Optimized Independent Set} or OIS, CA algorithm in Algo 1. Here, we approach the CA problem as an improvised vertex-coloring problem ensuring that no radio on any node in the original WMN graph \(G\) is assigned multiple channels. For a smooth discourse, let us consider an arbitrary radio \(r\) in the WMN. All the wireless links emanating from this radio will be represented in the E-MMCG \(G_c\) by a subset of vertices \(V_r\), that will form a \textit{clique} as every vertex element in \(V_r\) will be connected to every other vertex in the subset. The initial step is to partition the vertex set of the E-MMCG into ISs. This is done by traversing each node exactly once, and allotting it an IS. If a node can not be assigned to any of the existing ISs, a new IS is created of which it becomes the first node. If a node can be assigned to more than one ISs, an IS is chosen at random. Next, all nodes of an IS are assigned the same channel, and the channel to be assigned to the next IS is selected in a cyclic fashion. But, any two vertices in the clique \(V_r\) will never be a part of the same IS as they are pair-wise adjacent to each other in the E-MMCG, and this very fact forbids translating the CA problem into a corresponding simple vertex coloring problem. To overcome this handicap, we adopt a \textit{selective} vertex coloring approach. As all the vertices in \(V_r\) will lie in different ISs, depending upon the number of available channels and the cyclic channel assignment, they may or may not have been assigned different channels. Thus, after generating all the ISs we identify the color (channel) that has been assigned to the maximum number of vertices in \(V_r\).

We now provide \textbf{Algorithm 1} of RCA OIS Channel Assignment For \(G\).

#### Algorithm 1 RCA Optimised Independent Set CA

**Input:** \(G = (V, E), G_c = (V_c, E_c), CS = \{1,2,...M\}\)

**Output:** RCA OIS Channel Assignment For \(G\)

1. \(IS \leftarrow \text{FindIndependentSets}(G_c)\). \{\(IS\) : Set of mutually exclusive Independent Sets of vertices of \(G_c\)\}
2. \(Channel \in CS\), Channel \(\leftarrow 1\).
3. \textbf{for} \(IndSet \in IS\) \textbf{do}
4. \hspace{1em} \textbf{for} \(Node \in IndSet\) \textbf{do}
5. \hspace{2em} \(Node \leftarrow Channel\)
6. \hspace{1em} \textbf{end for}
7. \hspace{1em} \(Channel \leftarrow Channel\%M + 1\)
8. \hspace{1em} \textbf{end for}

\{ Let \(V_r\) be the subset of all vertices in \(V_c\) which denote a link emanating from a particular radio \(r\) in \(G\). Let \(C_{last}\) be the \textit{Channel} assigned to the last element processed in \(V_r\) \}
9. \(r \leftarrow C_{last}\) \{Facilitates improvised vertex coloring\}
10. \textbf{for} \(i \in V\) \textbf{do}
11. \hspace{1em} \(Num_i \leftarrow i\) \{Number the nodes from \((1,...,N)\}\}
12. \hspace{1em} \text{Determine} \(Ch_i\) and \(Adj_i\)
13. \hspace{1em} \textbf{end for}

\{Ensure Topology Preservation in \(G\)\}
14. \textbf{for} \(i \in V\) \textbf{do}
15. \hspace{1em} \textbf{for} \(j \in Adj_i\) \textbf{do}
16. \hspace{2em} \textbf{if} \((\text{Num}_i < \text{Num}_j)\) \&\& \((|Ch_i \cap Ch_j| == 0))\) \textbf{then}
17. \hspace{3em} \(Ch_j \leftarrow Ch_j + (c_{com}) - (c_{dif})\) \{ \((c_{com} \in Ch_i)\) \&\& \((c_{dif} \in Ch_j)\) \&\& \((\text{TID}(G)\text{ is minimum})\}\}
18. \hspace{2em} \textbf{end if}
19. \hspace{1em} \textbf{end for}
20. \hspace{1em} \textbf{end for}
21. \textit{Perform Radio Co-location Optimization in} \(G\) \{Steps described in Algo 2\}
topology, and may even lead to a disconnected graph $G$. It is thus of great importance to preserve the original WMN topology which reflects the intended physical span of the wireless network. Designing a generic topology preserving optimal CA algorithm is an established NP-hard problem \[12\]. Hence, the algorithm described in steps 10–20 of Algo \[1\] is a smart heuristic approach specifically tailored to ensure topology preservation after the initial channel assignment. The algorithm first sequentially orders the nodes of the WMN graph $G$, and assigns every node $i$ a number $Num_i$. It then determines for each node $i$ in $G$, the sets $(Ch_i)$ and $(Adj_i)$. Further, for every $i$ in $G$, every neighboring node $j$ in $Adj_i$ such that $Num_i < Num_j$, is scanned to determine if $i$ & $j$ share a common channel to communicate. If not, then the WMN topology is violated, and a forward correction technique is adopted to establish a connection between the two nodes and restore the topology. The constraint $Num_i < Num_j$ ensures that in every topology preserving channel re-assignment, a channel from node $i$ is picked and assigned to node $j$ i.e., a correction in the forward direction, thereby forbidding the possibility of a backward link disruption on a node while attempting to re-establish its connection on another link. Further, the choice of the $(c_{com}, c_{dif})$ pair, from $Ch_i$ and $Ch_j$ respectively, is predicated on a minimum TID value or a maximum decrease in the estimate of the prevalent interference.

The final and the most crucial step involves radio co-location interference mitigation, a performance enhancement feature which is the combined outcome of the use of E-MMCG model for initial channel assignment, and the post channel allocation radio co-location optimization function. Thus, the twin methods of restraining RCI have been employed in conjugation.

Radio co-location optimization functionality presented in Algo \[2\] commences by ascertaining $Ch_i$ and $Adj_i$ for each node $i$ of $G$. It explores $Ch_i$ of each node to determine if two or more spatially co-located radios (SCRs) have been assigned an identical channel to operate on. If so, it attempts to alleviate the RCI by re-assigning all such SCRs barring one, distinct channels from the list of all available channels (CS) ensuring that the final configuration results in a minimum TID value. One of the SCRs continues to operate on the channel it was originally assigned so as not to disrupt an existing wireless link of the node in context. After performing RCI mitigation, the function analyzes each wireless link of the WMN exactly once, to check if the current channel of the link can be replaced with an alternate channel $(c_{dif})$ from CS so that the overall TID estimate decreases and with an important caveat that the underlying WMN topology is preserved denoted by function $(NetTopPreserved())$. If a desirable channel replacement for a link is found, the current channel $(c_{ij})$ connecting the nodes $i$ & $j$ is removed from both $Ch_i$ & $Ch_j$, and the preferred channel $(c_{dif})$ is added to both.

The features described above, coupled with the characteristic that the ISSs are generated concurrently in OIS-CA result in ISSs of comparable cardinalities. In sharp contrast cardinalities of MISs generated consecutively, as in MaIS-CA, fail to provide for a balanced distribution of channels among radios. Table 1 illustrates the performance of RCA OIS CAs in terms of statistical evenness. OIS outperforms MalIS, and the following two aspects elicit this observation. Firstly, in OIS the difference between the cardinalities of any two sets of radios among $R_{C1}$, $R_{C2}$ & $R_{C3}$, never exceeds 35% and the difference between at least a pair of mentioned sets is always under 10%. This ensures a balanced channel assignment. Secondly, the default channel $C_1$ is not under utilized and is assigned to almost as many radios as channel $C_2$, occasioning and guaranteeing fairness in spectrum utilization. The relevance of an even statistical distribution, and fairness in channel utilization demonstrated by RCA OIS-CA is vindicated by the TID estimates depicted in Fig 1(a). The grid WMNs are of size $(N \times N)$, where $N \in \{3, ..., 10\}$, each node is equipped with 2 radios and 3 orthogonal channels are available. It can be inferred from the consistently lower TID estimates exhibited by RCA OIS-CA, as compared to MalIS-CA, that it is the more efficient CA scheme owing to its intelligent algorithm design. This theoretical conclusion will be substantiated by the experimental results presented in later sections.

B. Elevated Interference Zone Mitigation (EIZM) CA

We now propose the RCA EIZM algorithm pivoted primarily on the spatial characteristics of the endemic radio interference, but which factors in the statistical dimension as well. The motivating principle catalyzing the algorithm design is that the intensity of prevalent interference fluctuates within a wireless

Algorithm 2: Radio Co-location Optimization

**Input:** $G = (V, E), CS = \{1, 2, ..., M\}$

**Output:** Mitigate RCI in $G$ & minimize $TID(G)$

```plaintext
1: for $i \in V$ do
2: Determine $Ch_i$ and $Adj_i$
3: end for
4: for $i \in V$ do
5: if $(((j_1, j_2, ..., j_k, Channel) \in Ch_i)$ && $(j_1 = j_2 = ... = j_k = Channel))$ then
6: $j_1 \leftarrow Channel, j_2 \leftarrow c_2, ..., j_k \leftarrow c_k$ \{$(c_2, ..., c_k) \in CS$ are distinct if possible$\}$ && $(TID(G)$ is minimum$\}$
7: end if
8: end for
9: for $i \in V$ do
10: $Get c_{ij}$ \{Current channel of wireless link $(i, j)$\}
11: for $c_{dif} \in CS$ do
12: if $((c_{ij} \leftarrow c_{dif})$ && $(NetTopPreserved())$ && $(TID(G)$ decreases$)$ then
13: $Ch_i \leftarrow Ch_i + \{c_{dif}\} - \{c_{ij}\}$
14: $Ch_j \leftarrow Ch_j + \{c_{dif}\} - \{c_{ij}\}$
15: end if
16: end for
17: end for
18: end for
19: end for
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network, causing localized pockets of unusually high interference levels. We call the wireless links in the WMN which form the epicenter of such severe performance bottlenecks as the Elevated Interference Zones or EIZs. Taking a cue from the study on the impact of interference on a WMN in [13], we offer the argument that the EIZs impede the network performance drastically as they substantially degrade the signal to noise plus interference ratio (SINR) on neighboring links in the network. A WMN having a large number of links on which a data transmission experiences strong levels of interference, even though the communication over the remaining links exhibits a high SINR, will lead to a dismal aggregate network capacity owing to the inherent multi-hop nature of packet exchange among nodes. In contrast, a WMN in which all radio links experience a lower SINR will perform better than the former. Thus an EIZ is a particular wireless link in the WMN that may cause severe degradation of the network capacity. The question now remains as to how do we precisely characterize an EIZ for an accurate physical modeling? We contend that a wireless link with a high number of adjacent links is a potential EIZ, the extent of whose severity is predicated upon the channels allocated to it, and its neighboring links. The intuitive notion for such consideration is that the channel assignment on an EIZ tends to have an enormous impact on the network performance due to a high number of potential conflict links. A favorable channel assigned to an EIZ may significantly improve the overall network capacity while an ill-chosen channel may exacerbate the effects of interference manifold. We adopt a view that eroding the detrimental impact of interference on an EIZ will occasion a ripple effect that will certainly reduce the adverse effects of interference on its adjacent links.

We now translate our theoretical proposition into a feasible practical implementation i.e., correlate the concept of an EIZ in a WMN with its representation in the E-MMCG. An EIZ in the WMN is identified by its corresponding node in the E-MMCG, and by labeling E-MMCG nodes as EIZs, the algorithm pinpoints the respective performance bottleneck links in the WMN. The RCA EIZM-CA algorithm accepts the E-MMCG of a WMN as input, and considers EIZs to be the nodes with the maximal degree and nodes which share the maximal number of neighbors with an existing EIZ. The maximal degree node signifies a link with the maximum link-adjacency in a WMN and an obvious reference EIZ node to begin with. The subsequently chosen EIZ nodes are those which share the most number of mutual neighbors with the existing EIZ node. The process of EIZ selection should ideally be based on the SINR values of nodes. However, SINR values are a temporal or dynamic link quality parameter and can be ascertained only during active data transmissions. Thus, the improvised EIZ selection approach considers the theoretical TID estimates as an approximate measure of the impact of interference instead of the dynamic SINR values, and nodes with high TIDs are the first candidates to be labeled EIZs. Further, the scheme intelligently assigns channels to the EIZ nodes so that the detrimental impact of interference on the WMN, represented by the TID estimate, reduces. This is a spatial algorithm design strategy wherein the intense EIZs i.e., the maximal degree nodes in E-MMCG are efficiently assigned channels first. Thereafter the nodes which share the maximal number of mutual neighbors with them are visited and so forth, triggering an outward ripple of interference mitigation.

EIZM approach elucidated in Algo [3] employs a Breadth

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**Algorithm 3 RCA Elevated Interference Zone Mitigation CA**

**Input:** $G = (V, E), G_c=(V_c, E_c), CS = \{1, 2, \ldots, M\}$

**Output:** RCA EIZM Channel Assignment For $G$

1. Let $v_{\text{maximal}} \leftarrow \text{maximalDegNode}(V_c)$
2. $LS \leftarrow \text{LevelStructure}(v_{\text{maximal}}, G_c)$ \{LS : Set of level-sets generated by Breadth First Traversal of vertices of $G_c$\}
3. $\text{Channel} \in CS$, $\text{Channel} \leftarrow 1$
4. for $\text{LevSet} \in LS$ do
5. \hspace{1em} for $\text{Node} \in \text{LevSet}$ do
6. \hspace{2em} $\text{Node} \leftarrow \text{Channel}$
7. \hspace{1em} end for
8. $\text{Channel} \leftarrow \text{Channel} \% M + 1$
9. end for
10. for $\text{LevSet} \in LS$ do
11. \hspace{1em} $\text{PrevNode}_{EIZ} \leftarrow 0$
12. \hspace{1em} for $\text{Node} \in \text{LevSet}$ do
13. \hspace{2em} if $(\text{PrevNode}_{EIZ} \leftarrow 0)$ then
14. \hspace{3em} $\text{Let Node}_{EIZ} \leftarrow \text{maximalDegNode}(\text{LevSet})$
15. \hspace{3em} \{Maximal degree node in the Level Set is the initial EIZ node\}
16. \hspace{2em} else
17. \hspace{3em} $\text{Let Node}_{EIZ} \leftarrow \text{MaximalMutualNeighbor}(\text{LevSet}, \text{PrevNode}_{EIZ})$
18. \hspace{3em} end if
19. \hspace{2em} $\text{Node}_{EIZ} \leftarrow \text{Channel}, \text{such that TID}(G)$ is minimum
20. \hspace{2em} $\text{PrevNode}_{EIZ} \leftarrow \text{Node}_{EIZ}$
21. \hspace{1em} $\text{LevSet} \leftarrow \text{LevSet} - \{\text{Node}_{EIZ}\}$
22. end for
23. Ensure Topology Preservation in $G$ \{Perform steps 10 to 20 described in Algo [1]\}
24. Perform Radio Co-location Optimization in $G$ \{Steps described in Algo [2]\}
First Traversal (BFT) starting from a reference node, which could be a node representing a link to the Gateway or a specifically chosen node. We consider a maximal degree node \(v_{\text{maximal}}\), which is unarguably an EIZ, to be the reference. A Level Structure (LS) is generated, which is a partition of the vertex set \(V_c\) into subsets of vertexes that lie in the same level of the BFT i.e., vertices which are situated the same number of hop-counts away from \(v_{\text{maximal}}\) are placed in the same level. We term these subsets of the LS as level-sets. Next, to fashion a fair spectrum utilization, each level-set is assigned a channel chosen from CS in a cyclic manner. This step caters to the statistical aspects of interference alleviation, by attempting to maintain an equitable distribution of channels across radios in the WMN. In addition, vertices of level-sets which differ by a single level are assigned non-overlapping channels, thereby substantially reducing link conflicts. The next step entails processing each level-set, and assigning channels to the nodes within a level-set, iteratively. The EIZs are identified in each level-set. When a level-set is being processed for the first time, the maximal-degree node in the level-set determined by the function \(\text{MaximalDegNode}\), serves as the initial EIZ node. In subsequent iterations the function \(\text{MaximalMutualNeighbor}\) choses the node which boasts of the highest number of mutual neighbors with the previous EIZ node to be the current EIZ node. If there is more than one node to pick from, the node with the highest degree among them is selected as the next EIZ. Thereafter, the EIZ node is re-assigned a channel from CS which results in a minimum TID value. This step may or may not alter the initial assignment, depending upon the TID estimate. Upon final assignment, the EIZ node is removed from the level-set and aids in identifying the next EIZ node. After the initial channel allocation the algorithm ensures topology preservation through the steps described earlier in OIS-CA implementation. The last and the most important step is the RCI optimization proposed in Algo 2 which has also already been elaborated upon.

The illustrations presented in Fig 2 provide an insight into the functioning of the EIZM algorithm. Fig 2(a) is an E-MMCG representation of a sample WMN in which the reference node signifies a corresponding link to the Gateway in \(G\), and is denoted by \(GW\). Based on the proposed characteristics of an EIZ, the primary potential EIZ candidates are nodes \(B\) and \(D\), and upto a lesser extent, nodes \(C\) and \(F\). This inference is substantiated by the sequence of EIZ node identification carried out by EIZM scheme, depicted in Fig 2 (b). The number in the subscript of the node label is the sequence number of the order in which EIZ node were identified. The algorithm considers \(GW\) as the reference and performs a BFT, yielding \(B, D, C, A\) as the elements of the 1st level-set i.e., the set of nodes one hop away from \(GW\). Nodes of the 1st level-set are linked to \(GW\) through dotted lines in Fig 2(b). As expected, node \(B\) is the 1st EIZ, followed by \(C, D\) and \(A\). The 2nd level-set which comprises of all the remaining nodes, produces the sequence \(F, G, E, H\) and \(I\) of consecutive EIZ nodes. It may be argued that \(A\) was chosen as an EIZ before \(F\), despite the latter exhibiting stronger EIZ characteristics. The underlying reason is that node \(A\) is one hop away from \(GW\), an element of the 1st level-set, and thus processed before \(C\) which lies in the 2nd level-set. This however, is not an anomaly but a consequence of a conscious design choice to divide the E-MMCG nodes into level-sets. This technique serves the twin objectives of a fair distribution of channels among radios, and because of the channel initialization of each level-set in a cyclic manner, it ensures minimal conflict between nodes of consecutive level-sets, diminishing impact of interference. Hence, the EIZM algorithm maintains a fine balance between the spatial and statistical aspects of interference mitigation, and benefits by doing so.

The BFT approach is quite often used in CA schemes. For example in the BFS-CA algorithm suggested in [6], a BFT is performed on the multi-radio conflict graph or MCG of the WMN, starting from a Gateway node. The nodes are accessed in the increasing order of hop-count from the Gateway, and assigned channels. However, BFS-CA and other BFT based algorithms, do not take into account the existence of high interference zones, and hence do not prioritize their channel assignment based on the EIZ concept. Secondly, although BFS-CA processes nodes on the basis of hop-counts, it does not initialize nodes situated one hop-count away from each other with different channels. Thus, it fails to facilitate a balanced and fair channel distribution. Finally, like all other CA schemes, BFS-CA too fails to acknowledge RCI and take measures to alleviate it. Experimental results will demonstrate that EIZM scheme, designed in conformity with the proposed concepts, registers a network capacity which is even more than 2.5 times that of BFS-CA for a few test scenarios.

C. Time Complexities Of Proposed Algorithms

For a given a WMN graph \(G\) of \(n\) nodes and its E-MMCG \(G_c\) of \(m\) nodes, we suggest the computational costs of the proposed RCA CA schemes. Since both OIS-CA and EIZM-CA accept the E-MMCG \(G_c\) as input, their time complexities are a function of \(m\). In OIS-CA, generating the ISs takes \(O(m^2)\) time, as does the BFT in EIZM-CA. In contrast, the topology preservation technique operates on WMN graph \(G\) as input. It first numbers the nodes in \(G\) and then for each node, traverses its adjacent nodes. Thus it has a worst-case cost of \(O(n^2)\). Similarly, it can be derived that radio co-location optimization function has \(O(n^2)\) complexity as well. However, due to high number of conflict links in a MRMC WMN, the number of nodes in the E-MMCG are much greater than those
in the original WMN i.e., \( m \gg n \). Thus, it is reasonable to conclude that the overall time complexity of both the RCA CA algorithms is \( O(m^2) \).

V. Simulations, Results and Analysis

It is imperative that we prove the relevance of the proposed RCA CA schemes and validate the arguments their design is predicated on, through extensive experimental results. Our objectives are two-fold.

1) Demonstrate the significance of Radio Co-location Optimization: We highlight that RCI optimization functionality does substantially enhance a CA’s performance, consolidating the primary premise this study is based on. This is accomplished by comparing the instance of the proposed CA schemes that is non-RCA i.e., the CA generated before radio co-location optimization step, with the corresponding final RCA CA. The RCA CAs are denoted by \( OIS-CA \) & \( EIZM-CA \) while their non-RCA counterparts are represented by \( OIS-N-CA \) & \( EIZM-N-CA \) in the result illustrations.

2) Compare performance of RCA CAs with conventional CAs: We present experimental evidence to corroborate that RCA CAs significantly outperform the conventional CAs that do not ensure RCI alleviation and lack a spatio-statistical design. We employ MaIS-CA \cite{8} and BFS-CA \cite{6}, as the reference CAs against which we compare OIS-CA and EIZM-CA, respectively. The reference CAs are carefully chosen to demonstrate that despite a likeness in the underlying approach of the CA pairs OIS-CA & MaIS-CA, and EIZM-CA & BFS-CA, elaborated upon earlier, the RCA algorithms fare remarkably better.

A. Simulation Parameters

We perform exhaustive simulations in ns-3 \cite{14} to gauge the performance of CAs deployed on the following two WMN topologies.

- A random WMN of 50 nodes spread across an area of \( 1500m \times 1500m \).

The choice of a grid WMN is motivated by the fact that they fare better than random layouts in terms of coverage area and mesh network capacity \cite{15}, resulting in an ideal topology for CA performance evaluation. The simulated environment of a large WMN comprising of 50 randomly placed nodes is also a relevant layout, as it resembles a real-world WMN deployment which is less likely to conform to a grid pattern. The large number of nodes spread over a wide area facilitates long distance data transmissions requiring multiple-hops between nodes placed on the fringes of the network, a scenario vital for estimating the efficiency of a CA in performing such transmissions. For ease of reference, grid WMN and random WMN are abbreviated as \( GWMN \) and \( RWMN \), respectively. The simulation parameters are presented in Table II. Each multi-hop traffic flow transmits a datafile from the source to the destination. For the grid WMN, we equip each node with 2 radios and CA schemes have 3 orthogonal channels at their disposal. Given the enormity and complexity of the random WMN we scale up the technical specifications. Thus each node has 3 radios, and each radio can be allotted one of 4 orthogonal channels. We carry out two set of simulations employing TCP and UDP as the underlying transport layer protocols. We leverage the built-in ns-3 models of BulkSendApplication and UdpClientServer for TCP and UDP implementations, respectively. TCP simulations are aimed at estimating the Aggregate Network Throughput, which we henceforth simply refer to as the Throughput, for each scenario. UDP simulations are employed to determine the packet loss ratio (PLR) and the mean delay (MD) for a test-scenario.

\[
\text{TABLE II: ns-3 Simulation Parameters}
\]

| Parameters                | Values                       |
|---------------------------|------------------------------|
| Radios/Node               | GWMN: 2, RWMN: 3             |
| Range Of Radios           | 250 mts                      |
| IEEE Protocol Standard    | GWMN: 802.11g, RWMN: 802.11n |
| Available Orthogonal Channels | GWMN: 3 (2.4 Ghz), RWMN: 4 (5 Ghz) |
| Transmitted File Size     | GWMN: 10 MB, RWMN: 1 MB      |
| Maximum 802.11g/n Phy Datrate | 54 Mbps                      |
| Maximum Segment Size (TCP) | 1 KB                         |
| Packet Size (UDP)         | GWMN: 1 KB, RWMN: 512 Bytes  |
| MAC Fragmentation Threshold | 2200 Bytes                   |
| RTS/CTS                   | Enabled                      |
| Packet Interval (UDP)     | 50 ms                        |
| Routing Protocol Used     | OLSR                         |
| Loss Model                | Range Propagation            |
| Rate Control              | Constant Rate                |

B. Data Traffic Characteristics

Tailoring an ideal set of data traffic characteristics is a crucial step so as to aptly highlight the performance bottlenecks caused by the endemic interference and to explicitly demonstrate the mitigation of their adverse impact on the WMN performance by the deployed CA. Since, multi-hop data flows are an inherent feature of WMNs, we simulate a variety of test scenarios for both the WMN topologies which employ the following multi-hop flows.

1) Grid WMN: 4-Hop Flows or 4HFs are established from the first node (source) to the last node (sink), of each row and each column of the grid. 8-Hop Flows or 8HFs are set up between the diagonal nodes of the grid.

2) Random WMN: We create a plethora of multi-hop flows between nodes which are 3 to 10 hops away, ensuring that the paths of many of these flows intersect to occasion comprehensive interference test-scenarios.

C. Test Scenarios

Various combinations of the multi-hop flows described above are devised to generate test-scenarios, that reflect both, a
sectional view and a comprehensive view, of the intensity, impact and alleviation of the prevalent interference. Test-cases for both the WMN layouts are listed below.

1) Grid WMN:
(a) $D2$ : Both 8HDFs concurrently.
(b) $H5$ : All five 4HFs concurrently in the horizontal direction.
(c) $V5$ : All five 4HFs concurrently in the vertical direction.
(d) $H4V4$ : Variety of eight concurrent flows, which include various combinations of 4HFs.
(e) $H5V5$ : Ten concurrent 4HFs viz. H5 & V5.
(f) $H5V5D2$ : Twelve concurrent flows viz. D2, H5 & V5.

Test cases (a,b & c) offer a directional perspective of CA performance, while scenarios (c, d & e) form the exhaustive benchmarks on which the overall performance of CA can be assessed.

2) Random WMN: Given the random placement of nodes, the test-scenarios include a combination of concurrent multi-hop flows of varying hop counts. 4, 8, 12, 16 and 20 concurrent multi-hop flows were established, where the number of simultaneous data flows represents a test-case viz. TC4, TC8, TC12, TC16 & TC20. As the number of concurrent flows increases, the interference dynamics become more complex. Thus test-cases TC12, TC16 and TC20 are ideal to gauge CA efficiency in terms of network performance metrics.

D. Results and Analysis

Rigorous simulations were run for the test-cases described above, and the observed values of performance metrics viz. Throughput (Mbps), PLR (% of packets lost) and MD ($\mu$seconds) are now presented for a thorough analysis of the performance of the proposed RCA CAs.

1) Throughput: The throughput results for simulations run on GWMN and RWMN topologies are depicted in Figs 3, 4, 5 & 6. For statistical reliability 99% Confidence Interval bars have been marked for the recorded Throughput value of each test-case. Our first objective is met through a conspicuous inference from the listed plots, that the non-RCA version of the proposed CAs registers much lower throughput than the RCA version, highlighting the efficacy of radio co-location optimization feature of the RCA CAs and consolidating our theoretical contention that RCI mitigation enhances the network capacity significantly. EIZM-CA registers a maximum capacity enhancement of 132% for scenario H5V5D2 in GWMN and about 48% for scenario TC20 in RWMN, over EIZM-N-CA. Improvements exhibited by OIS-CA over OIS-N-CA for identical scenarios are 48% and 8%, respectively. Let us now analyze the performance of the RCA CAs in comparison to the reference CAs. It is discernible that RCA CAs outperform both MalS-CA and BFS-CA by a significant margin. This is evident from the substantial increase in Throughput in RCA CA deployments, displayed in Table III.

EIZM-CA turns out to be the better of the two high perfor-
mance RCA CAs, however OIS-CA fares quite better than both BFS-CA and MaIS-CA as well. Another interesting observation is that the non-RCA CAs perform decidedly better than both of the reference schemes in the RWMN simulations, but not in the GWMN. Hence, no definitive conclusions can be made between non-RCA CAs and the reference CAs, which highlights the importance of RCI alleviation in enhancing CA performance. Further, OIS-N-CA performs slightly better than OIS-CA in test-case TC8 in RWMN. However, this scenario projects a partial or sectional view of the RWMN and the upset in results does not amount to a reversal in the expected trend. This momentary aberration is remedied in the remaining test-cases, where OIS-CA continues to outperform OIS-N-CA. Another noteworthy point is the spatial impact of interference in GWMN where the scenarios H5 and V5 include an equal number of (five) concurrent 4HFs, along the rows and columns of the grid, respectively. Yet in Fig 7 it can be observed that for EIZM-CA, scenario H5 records a higher throughput than V5 i.e., lower impact of interference is experienced by transmissions along the rows, while for EIZM-N-CA the situation is reversed i.e., transmissions along the columns register higher throughput.

2) Packet Loss Ratio: PLR performance metric observations are in absolute conformity with the network capacity results. For the RWMN layout, we present PLR for all the test-cases, however for the GWMN topology, results of the three comprehensive test-cases viz., H4V4, H5V5 and H5V5D2, are presented as the PLR in other scenarios was negligible. In Figs 7 and 8 it can be noticed that both the RCA CAs experience the minimum packet loss. Similar to the result trends in throughput, RCA versions of CA show higher resilience to interference induced packet loss, leveraging the benefits of RCI mitigation functionality. Thus, PLR estimates also highlight the enhancement in performance of deployed RCA CAS owing to their twin capabilities of RCI alleviation and spatio-statistical design. For a quantitative analysis, the % reduction in PLR effected by RCA CAs in comparison to the reference CA approaches is elicited in Table IV.

3) Mean Delay: Multi-hop flows are an inherent characteristic of the WMNs, hence it is of great relevance to observe the

### Table III: Enhancement in network capacity through RCA CAs

| Comparing CAs     | % increase in Throughput in TC |
|-------------------|-------------------------------|
|                   | TC16 | TC20 | H5V5 | H5V5D2 |
| EIZM-CA vs BFS-CA | 142  | 149  | 96   | 106    |
| EIZM-CA vs MaIS-CA| 74   | 68   | 72   | 72     |
| OIS-CA vs BFS-CA  | 72   | 81   | 64   | 67     |
| OIS-CA vs MaIS-CA | 24   | 22   | 43   | 40     |

### Table IV: Reduction in PLR through RCA CAs

| Comparing CAs     | % decrease in PLR in TC |
|-------------------|-------------------------|
|                   | TC16 | TC20 | H5V5 | H5V5D2 |
| EIZM-CA vs BFS-CA | 81   | 78   | 76   | 67     |
| EIZM-CA vs MaIS-CA| 9    | 4    | 8    | 11     |
| OIS-CA vs BFS-CA  | 88   | 77   | 73   | 76     |
| OIS-CA vs MaIS-CA | 41   | -2   | -6.5 | 34     |

There are three minor upsets in the observed trends, two between OIS-CA and MaIS-CA, where the latter performs marginally better in test cases TC20 and H5V5. But these slight reversals are mere exceptions in the observed pattern, and do little to discredit the improvement exhibited by RCA CAs. Further, between the two RCA CAs, EIZM-CA proves to be the better scheme in terms of packets lost during transmission.

### Fig. 7: PLR of RCA CAs in GWMN

### Fig. 8: PLR of RCA CAs in RWMN

### Fig. 9: MD of RCA CAs in GWMN

### Fig. 10: MD of RCA CAs in RWMN
ease with which, for a CA implementation, data is transmitted across distant nodes in the WMN that are numerous hop-counts apart, especially under high network traffic loads. The recorded MD values are illustrated in Figs 9 and 10 for simulations run on GWMN and RWMN topologies, respectively. The delay characteristics of all the CAs are similar to those observed in PLR results. RCA CAs reduce the MD time considerably, especially in comparison to BFS-CA where the % reduction in delay times for scenario TC20 is 67% and 68% for OIS-CA and EIZM-CA, respectively. This observation follows from the notion that a low PLR generally leads to a small packet delays. There are no noticeable reversals and RCA CAs consistently perform better than the reference CAs. Further, between the two RCA CAs, none has a distinct edge over the other. While OIS-CA exhibits small delay times for some test-cases, EIZM-CA registers a greater reduction in MD for others.

**TABLE V: Reduction in MD through RCA CAs**

| Comparing CAs | TC16 | TC20 | H5V5 | H5V5D2 |
|---------------|------|------|-------|--------|
| EIZM-CA vs BFS-CA | 70   | 68   | 31    | 31     |
| EIZM-CA vs OIS-CA | 28   | 16   | 8     | 10     |
| OIS-CA vs BFS-CA | 66   | 67   | 27    | 28     |
| OIS-CA vs MalS-CA | 19   | 11   | 3     | 6      |

These findings provide an experimental validation to the emphasis we have laid on the spatio-statistical design of CA algorithms which is further improved through RCI alleviation measures.

**VI. CONCLUSIONS**

Having thoroughly deliberated over the performance of RCA CAs, we now make some sound logical conclusions. First, RCI prevalent in a WMN has a significant adverse impact on the network capacity, and its mitigation leads to enhanced Throughput and reduced PLR in a wireless network. Thus RCI mitigation ought to be a primary consideration in a CA scheme. Second, a prudent CA design that is tuned to the spatio-statistical aspects of interference alleviation will be more effective in restraining the detrimental effects of interference. Further, a CA scheme which which caters to both spatial and statistical dimensions, such as EIZM-CA, stands to fare quite better than one which considers only one of the aspects in its design, such as OIS-CA. On the subject of the performance of the proposed RCA CAs, it can be unarguably concluded that they are significantly better than the reference CA schemes in terms of Throughput, PLR and MD. They are high-performance CAs which enhance network capacity tremendously, are resilient to packet loss, and reduce data propagation delays.

Considering the average, EIZM-CA outperforms OIS-CA in terms of network capacity, by 45% and 11% in RWMN and GWMN layouts, respectively. The two RCA CAs are at par with respect to packet mean delay and PLR. The better performance of OIS-CA in GWMN can be attributed to the structured layout of a grid which facilitates a proportional distribution of channels across radios, unlike RWMN which is a large network of randomly placed nodes. EIZM-CA registers high performance in both WMN topologies, regardless of the layout. Clearly, EIZM-CA is the more efficient and better performing CA algorithm of the two, which it owes to its spatio-statistical design coupled with the feature of RCI mitigation.

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