Planning with Joint Clustering in Multi-hop Wireless Mesh and Sensor Networks

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***Abstract*—Wide spread deployment of wireless mesh networks for broadband access requires careful deployment and planning in terms of laying down the network infrastructure. Deploying such networks comes with some major inter-related issues including capacity planning, scalability and access reliability. Planning includes determining the number of gateways, optimal placement of gateways and relay nodes, maximizing coverage while minimizing the operational cost.**

This paper focuses on a planning approach that aims at increasing access fairness and fault tolerance using an overlapping clustering technique. It provides alternate paths for nodes residing at the edge of the clusters and mitigates upstream blocking towards the gateways to control delay, congestion and loss rate.

***Keywords*-wireless mesh network; clustering; wireless deployment; gateway placement;**

I. INTRODUCTION

The demand for seamless broad-band wireless Internet access has been the major driving force behind the development of multi-hop wireless mesh networks (WMNs) [1]. Wireless mesh networks combine several existing technologies and concepts from cellular, ad hoc, and sensor networks to improve network coverage, easy of deployment and better throughput. The shared wireless nature of the medium makes them more susceptible to failure. Transmission link failure, in which a wireless link experience an excessive loss rate or prolonged delays, is a common case of failure. This is mainly due to outdoor noise, interferences, multi-path fading, contention and congestion. Wireless mesh networks may also be subject to a variety of other faults including faults in network elements and protocol faults [2]. These faults result in low throughput and excessive delay or no connection at all. Some faults that are supposed to recover from path failure may create routing loops or a black holes. However, these faults can be mitigated or prevented by a careful and robust planning.

For a successful deployment of WMNs in such an environment, it is essential to provide certain resilience to the network connectivity during planning and deployment to avoid potential failures [3]. WMNs planning involves several interdependent factors that include network topology, network coverage, traffic demand, and capacity assignment. The optimal number of gateways and their locations have to be determined in advance and before deployment.

Gateway placement has a significant impact on the overall network performance including its financial viability and access reliability. In WMNs, traffic congestion is mostly due to up-stream aggregate traffic heading towards a gateway and that can be controlled by proper placement of gateways. While minimizing the number of gateways will reduce the deployment cost, fewer gateways will increase the average hop distance and consequently increases the average delay and the average relay load of the intermediate routers. Finding the optimal number of gateways can formulate as an optimization problem in which an objective function minimizes the number of gateways subject to a set of QoS requirements.

The gateway placement problem is similar to the clustering problem. Clustering has been studied extensively in the context of operation research with different objective functions and optimization goals. One of the main distinctions among clustering techniques is in their objective function. In the context of wireless mesh works, a set of more complicated and dynamic objective functions is involved in the clustering The set could include cluster size, number of clusters, hop count, and relay load. Given a significant portion of delay a packet suffers is associated with the hop count the packet travels, it is important to put a limit on the hop count towards a gateway and then optimize the other objectives.

In this paper, the optimal layout of the network has been integrated to the planning phase of a WMN deployment. It will allow diverse routing and fault-tolerant provisioning, particularly for links that face higher blocking probability to access a gateway. Generally, an edge node of a cluster faces more blocking probability and hence higher delay and loss rate than nodes closer to the cluster head. A new clustering technique is introduced by which the gateway placement algorithm allows redundant cluster membership to improve access reliability while keeping the optimality intact.

The rest of the paper is organized as follows. Section II summarizes related work with respect to the gateway placement problem in wireless mesh networks. Section III covers basic preliminaries and definitions. Section IV presents a new network clustering techniques based on maximal independent sets. Section V extends the clustering algorithm of Section IV for joint cluster membership for disadvantaged nodes. Section VII concludes the paper.

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II. RELATED WORK

Link failure in a wireless network is commonly caused due to interference in the medium or traffic congestion and on rarer occasion due to the radio malfunction.

Fault tolerance has been getting a lot of attention in the area of sensory networks [2], due to the higher node failure rate, large scale of the network and the desire to increase automation. Fault recovery in such networks has been addressed in terms of routing [4], topology control [5], power assignment [6] and channel assignment [7], [8].

On the other hand, fault tolerance in wireless mesh networks, which are more stable than sensory networks, has been studied in the context of networking layer using routing protocols [9]. The routing protocols finds an alternate path to route a packet from a source to a destination if the primary path fails. However, all routing algorithms assume some route redundancy in the underlying network topology, which is more apparent in WMNs than in sensor networks.

In [10] the authors discuss fault tolerance with respect to gateway placements. To address node and link failures they modify the gateway placement LP formulation and add a fault tolerance constraint to ensure over-provisioning via multiple independent paths. They propose a greedy heuristic to address gateway placement that iteratively picks up nodes that increasingly satisfy the traffic demand without necessarily selecting a node that satisfies the most demand. Therefore, in this work we focus on building wireless network that are fault tolerant at the network topological level.

A. Gateway Placement Problem

In the following, we give an overview of the gateway placement problem and provide the most common approaches proposed in the context of wireless mesh networks.

1) Placement with Integer Linear Programming: The optimal placement can be obtained by minimizing the number of clusters(k in Equation 8) subject to a set of constraints such maximum cluster size, maximum cluster radius, etc. The combinatoric algorithm checks all possible combinations to find a solution that satisfies all the QoS constraints. This approach is prohibitively expensive and does not scale beyond very small network.

2) Placement with Greedy Approach: In [10], the authors suggest to place the gateway simply at a location where it satisfies the most traffic demand subject to the capacity of the gateway and relay nodes. However their greedy approach can lead to an imbalance loading of certain gateway and does not support all the quality of service requirements.

3) Placement with Iterative Clustering: The earliest work that directly addressed the placement of gateways in a wireless mesh network [11] describes the problem as a capacitate facility location problem with additional constraints. The author solves the placement problem by breaking it into two sub problems. First a polynomial time approximation algorithm that cuts the network into disjoint clusters using a shifting algorithm or a greedy dominating independent set algorithm. Once the initial clustering is completed, each cluster is evaluated to that ensure QoS constraints are met. If the QoS is violated, then the cluster is sub-divided into smaller clusters at the node where QoS is violated. However, for the solution to work, it is assumed that the underlying medium access protocol is TDMA(Time-Division Multiple Access). TDMA protocols require synchronization, which is hard to achieve in large multi-hop wireless networks. Additionally, the proposed solution generates higher fragmented clusters.

4) Placement with Recursive Clustering: Similar to [11], in [12], the authors form a cluster and a spanning tree within each cluster to obtain a near optimal solution. They propose a recursive algorithm that builds a clustering and then admits it into the solution only if it meets the QoS constraints. The algorithms is able to produce lesser number of clusters than those in [11]. However, the cluster sizes have a large variance and the clustering does not vary uniformly when with a uniform change in QoS constraints.

5) Split-Merge-Shift: The Split-Merge-Shift [13] starts with an initial clustering graph and then it goes through a few iterations of *Split*, *Merge*, and *Shift* operations to form the final clustering. The algorithm does not necessarily generate an optimal solution initially, but over a set of iterative Split-Merge-Shift operation it converges close to optimality.

III. PRELIMINARIES

In planning, deployment or updating a wireless network, it is often necessary to determine the transmission range with an acceptable throughput. While there are many factors that affect the tranmission range, the theoretical transmission distance can be obtained from a few key specifications.

Definition 1 (Transmission Range): Given the transmission power P_t, the receiving power P_r, the transmission range d can be calculated as,

$$d = \frac{\lambda}{4\pi}\sqrt{\frac{P_t G_t G_r}{P_r F_t}} \tag{1}$$

where G_t, G_r are the transmitting and receiving gains with an acceptable loss factor F_t and λ is the wavelength of the communication channel.

Definition 2 (Transmittance Matrix): We define the binary transmittance matrix $T = [t_{ij}]$ as

$$t_{ij} = \begin{cases} 1 & \text{if} \quad d_{ij} \le t_r, \quad i \ne j \\ 0 & \text{otherwise.} \end{cases} \qquad 1 \le i, j \le N \tag{2}$$

where d_{ij} be the Euclidian distance between node i and node j obtained from Equation 1.

Definition 3 (Reachability Matrix): The h-hop binary reachability matrix $R_h = [r_{ij}]$ is defined as

$$R_h = T^1 \vee T^2 \vee \cdots \vee T^h = \bigvee_{k=1}^{h} T^k, \tag{3}$$

where $\vee$ is the binary OR operation, and

$$r_{ij} = \begin{cases} 1 & \text{if node } i \text{ is at most } h \text{ hops away from} \\ & \text{node } j,\ i \ne j \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

Definition 4 (Hop Count Matrix): The entries of the hop count matrix $H = [h_{ij}]$ give the hop distance between nodes within the reachability range such that,

$$h_{ij} = \begin{cases} k & \text{if node } j \text{ is within } k \leq h \text{ hops from node } i \\ 0 & \text{otherwise.} \end{cases} \tag{5}$$

where $h = \max\{h_{ij} \mid 1 \leq i, j \leq N\}$.

Corollary 1: The reachability matrix $R_h = [r_{ij}]$ can be obtained from the hop-count matrix H as,

$$r_{ij} = \begin{cases} 1 & \text{if } h_{ij} > 0 \\ 0 & \text{otherwise.} \end{cases} \tag{6}$$

Definition 5 (Cluster): A cluster $C(V', E') \subseteq G(V, E)$ is an acyclic sub graph of G such that, $V' \subseteq V$ and $E' \subseteq E$.

Definition 6 (Clustering): A clustering is a way of partitioning graph $G(V, E)$ and can be formally defined as a set of clusters Ω, where,

$$\Omega = \{C_1, C_2, \cdots, C_k\}, \quad 1 \leq k \leq N, \tag{7}$$

with the following properties:

$$\begin{cases} P_1 : & \bigcap_{i=1}^{k} C_i = \emptyset \\ P_2 : & \bigcup_{i=1}^{k} C_i = G \\ P_3 : & V(\Omega) = V(G) \\ P_4 : & E(\Omega) = \bigcup_{i=1}^{k} E(C_i) \subseteq E(G). \end{cases} \tag{8}$$

Property P_1 guarantees that clusters are independent with no nodes in common. Relaxing this property allows overlapping clusters. Ω can be represented by an $N \times N$ asymmetric binary matrix with k non-zero rows, each representing a cluster with exactly a 1 on each column, characterizing each node to belong only to one cluster. Formally,

$$\Omega_{N \times N} = [\omega_{ij}] \in \{0, 1\}$$

with the following constraints,

$$\begin{aligned} (a) : &\quad \sum_{i=1}^{N} w_{ij} = 1, \quad 1 \leq j \leq N \\ (b) : &\quad \sum_{j=1}^{N} w_{ij} > 0, \quad \text{for some } i \end{aligned} \tag{9}$$

Constraint (a) guarantees that each node belongs only to one cluster, and constraint (b) makes node i as a cluster head with its member nodes j, where $\omega_{ij} = 1$ $(1 \leq j \leq N)$.

Later, in Section V, we relax the property P_1 in Equation 8 and its corresponding constraint (a) in Equation 9 to allow a node to participate in more than one cluster.

Generally, clustering formation and optimal placement of gateways (cluster heads) with some QoS constraints is known to be an $\mathcal{NP}$-hard problem [14]. Several heuristic are proposed in [11], [10], [12] and [13] to place gateways efficiently in a given network. However limited work has been done to allow fault-tolerant through joint memberships.

While ad hoc routing algorithms such as AODV (Ad hoc On-demand Distance Vector) and some of its variations can be used to route packets in multi-hop wireless mesh networks, generally they face a few shortcomings when directly applied to WMNs. First, their throughput performance does not typically scale to meet the expectation, particularly for real-time applications that are delay-sensitive or even loss-sensitive for data transmission. Their effective performance in terms of QoS requirements such delay, loss and jitter depends strongly on the underlying topology and the transmission range. Second, unlike ad hoc networks, where the traffic flows between arbitrary nodes, WMN traffic is either to or from a designated gateway (similar to a cellular system). A WMN routing algorithm must exploit this property to gain efficiency, which is the intention of this paper. Third, ad hoc routing algorithms are designed to deal with the possibility of highly mobile nodes and that requires a significant amount of overhead for route discovery, mobility and maintenance. On the other hand, WMNs routers have minimal mobility. This is yet another characteristic that can be exploited for efficiency. Finally, in terms of planning, ad hoc network planning is mostly done manually without any systematic approach, and often without paying attention to the overall system cost.

Because of their relatively fix position (or change of position is limited within a certain range) of WMN nodes, the implication is that the routing paths can be created that are likely to be stable. This will substantially reduce the routing overhead. The most commonly used topology for WMNs is a grid layout which is due to the layout of building and blocks. The relatively stationary topology of WMNs suggests that we can develop a more simplified routing algorithm along with a systematic approach to the planning and deployment. All these necessitate a different approach to the planning, deployment, and routing in WMNs which is the focus of this paper.

IV. PLANNING WITH DISJOINT CLUSTERING

By strictly applying property P_1 in Equation 8 along with constraint (a) in Equation 9, a clustering matrix in the form of Equation 2 can be formulated to represent an optimal set non-overlapping clusters covering the mesh network.

One of the important QoS requirements in WMNs is to determine the maximum number of hops a packet can travel before reaching its intended destination (gateway). For that, we form the h-hop reachability matrix R_h from Equation 3 that identifies the reachability set for each node on its rows.

This can be viewed as an initial clustering (trivial clusters) in which every node is considered to be a cluster head with all its members within h-hop distance. Clearly, this will create the maximum possible number of clusters (N) with maximum overlap amongst them. However, condition P_1 in Equation 8 is not satisfied for non-overlapping clusters. To satisfy property P_1, we introduce a *cluster graph* in which cluster C_i is connected to cluster C_j if $C_i \cap C_j = \emptyset$, $1 \leq i, j \leq N, i \neq j$. We further define the corresponding *clustering overlap matrix* as follows.

Definition 7 (Clustering Overlap Matrix): The entries of the clustering overlap Matrix, $O = [o_{ij}]$ is defines as,

$$o_{ij} = \begin{cases} \sum_{k=1}^{N} r_{ik} \wedge r_{jk} & i \neq j \\ 0 & i = j \end{cases} \quad 1 \leq i, j \leq N, \tag{10}$$

where $\wedge$ is the binary operation AND, and o_{ij} is the inner product of row i and row j of R_h. In effect o_{ij} gives the number of common nodes in two adjacent clusters headed by nodes i and j are considered two cluster heads. We define the adjacency clustering matrix $A = [a_{ij}]$ that describes relationships between clusters as follows.

Definition 8 (Clustering Adjacency Matrix): The clustering adjacency matrix $A = [a_{ij}]$ is defined as,

$$a_{ij} = \begin{cases} 1 & \text{if } o_{ij} \geq I_c \neq 0 \\ 0 & \text{otherwise.} \end{cases} \tag{11}$$

For disjoint clustering, first, we consider the case where $I_c = 1$. We start with the transmission matrix T in Equation 2 and a maximum clustering radius of h. We compute the reachability matrix within h-hop distance for each node according to Equation 3. The clustering adjacency matrix A identifies the relationship between potential clusters in terms of node sharing. We define matrix A' as the complement of A where,

$$a'_{ij} = \begin{cases} 1 & \text{if } a_{i,j} = 0 \\ 0 & \text{if } a_{i,j} = 1 \end{cases} \tag{12}$$

A' identifies all *pair-wise* disjoint clusters.

Definition 9 (Inter Cluster Distance): Inter cluster distance D_h is defined as the maximum number of hops between any two clusters.

To find the optimal location of cluster heads with maximum coverage, one has to find the maximum clique (maximum complete subgraph) of the graph associated with the adjacency matric A'. We use the Algorithm original developed by [15] to find the largest clique (complete subgraph). The current implementation of the algorithm searches for maximal independent vertex sets in the complementer graph. Given we have applied the constraint of hop-count h on each cluster, depending on the network topology, the algorithm does not necessarily cover all the nodes in the clustering.

Consider the 100-node mesh network of Figure 1. The initial clustering is shown in Figure 2 in which 8 gateways optimally cover the network with maximum hop count $h = 2$. The initial clustering does not cover nodes all the nodes mainly due to the *inter-cluster* constraints applies. For example, nodes $\{41, 45, 48, 52, 55, 57, 60, 64, 66, 73, 79, 81, 82\}$ have not been assigned to any of the clusters due to: (i) the maximum 2-hop coverage ($h = 2$) by the cluster heads, and (ii) the inter-cluster distance $I_c = 1$, i.e., neighboring clusters are at least one hop away from each other. However, uncovered nodes nodes are at most h hops away from a nearby cluster. For that we identify the *inter-cluster* distance matrix for the above clustering algorithm.

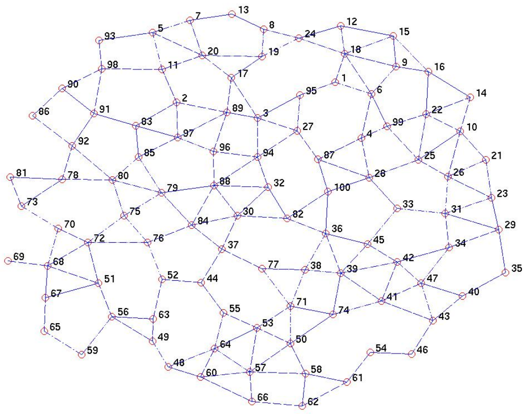


Fig. 1. A 100-node mesh network.

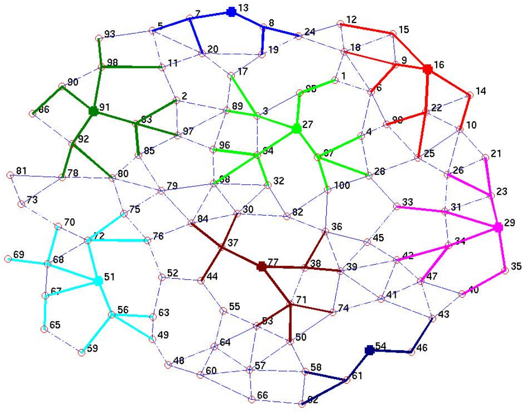


Fig. 2. Initial clustering with $h = 2$ and I_c=1.

Theorem 1: A node is either a cluster head or at most $2h$ hops away from a cluster head.

Proof: Given, the clustering algorithm forms only disjoint clusters, there are two cases.

If $\bigcup_{i=1}^{k} C_i = G$, then the clustering algorithm covers all nodes in the network and Property P_2 holds. Every node is within h hops from a cluster head and no nodes lies between two adjacent clusters, and hence $D_h = 1$.

If $\bigcup_{i=1}^{k} C_i \neq G$, then there is at least one node that does not belong to any of the clusters. Let $v \in G$ but $v \notin \bigcup_{i=1}^{k} C_i$ be such a node. Let the closest cluster to v be C_i with its cluster head node u. The h-hop reachability set of v is either disjoint or it has some nodes in common with the h-hop reachability set of u. Let $R_h(v)$ and $R_h(u)$ be the h-hop reachability sets for node v and u, respectively.

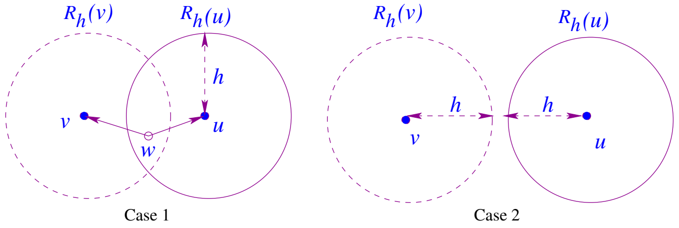
- Case 1: $R_h(v) \cap R_h(u) \neq \emptyset$. Let w be a common node in both reachability sets. Then the hop distance $H(v, w) \leq h$ and the hop distance $H(u, w) \leq h$. Hence $H(u, v) \leq 2h$.
- Case 2: $R_h(v) \cap R_h(u) = \emptyset$. Then v by itself constitutes an independent reachability set within its h radius and forms an independent cluster.

■

From Theorem 1, we can conclude the following corollaries.

Corollary 2: The maximum inter-cluster distance $D_h = h$.

Corollary 3: A node that has not been assigned to any clusters is at most h hops away from a neighboring cluster.



Case 1

Case 2

Fig. 3. Inter-cluster distance.

This is shown in Figure 2 in which nodes $\{41, 45, 48, 52, 55, 57, 60, 64, 66, 73, 79, 81, 82\}$ are either one hop or two hops away from a neighboring cluster, where $h = 2$. After the initial clustering, we will find the nearest cluster for the remaining nodes them to join. This is shown in Figure 4. Therefore, the radius of the final clustering is at most $2h = 4$ hops. While the inter-cluster distance $I_c = 1$ is one hop among the neighboring clusters, due to the network topology some clusters are affected by the residual nodes left out from the constraint h in algorithm 1.

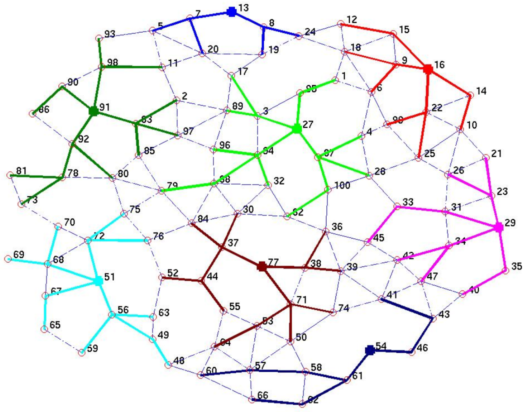


Fig. 4. Final disjoint clustering, $2 \leq h \leq 4, I_c = 1$.

Algorithm 1: Disjoint Clustering

```
Input : Transmittance Matrix $T$, $h$, $I_c = 1$
Output: Array $C$ of cluster heads
1 Calculate $R_h = \bigvee_{k=1}^{h} T^k$                      Eqn. 6
2 Calculate $o_{ij} = \sum_{k=1}^{N} r_{ik} \wedge r_{jk}$     Eqn. 10
  $1 \leq i, j \leq N$
3 Calculate $A$ from $O$ for $I_c = 1$                          Eqn. 11
4 Calculate $A'$ from $A$
5 Use the maximal independent set [15] to identify the
  cluster heads.
6 Form clusters by incorporating the reachability set (from
  $R_h$) for each cluster head.
7 Assign nodes outsides clusters to the closest cluster.
```

A. *Analysis*

The processing time involved in Steps 1-4 in Algorithm 1 are all based on two-dimensional matrices (mostly sparse matrices) and bounded by $O(N^2)$. The processing time and memory space in step 5 are bounded by $O(N + m)$ and $O(Nm\delta)$, respectively, where N is the number of nodes, m is the number of edges and δ is the maximal independent sets of the graph [15].

V. PLANNING WITH JOINT CLUSTERING

By relaxing property P_1 in Equation 8 and constraint (a) in Equation 9, we can obtain clusters that can share available bandwidth at the edge of clusters. Nodes at the edge of clusters belong to more than on cluster simply because they are in disadvantage positions as far as gateway access is concerned. They can dynamically switch their cluster membership due to a weak or bad connection at the edge of each cluster. This can be achieved in two ways; i) making $D_h = 1$ and allow the inter-cluster links be shared by the neighboring clusters, or ii) make clusters overlap by one or more hops. Note that the objective of this paper is to compensate access disparity with access redundancy for those nodes further away from a gateway to improve their throughput.

In this clustering scheme, nodes that are h hops away from a gateway have memberships in more than one cluster. The joint clustering algorithm is simply an extention of disjoint clustering algorithm with inter-cluster nodes having at least dual membership in neighboring clusters. This is shown in Algorithm 2. The difference between Algorithms 1 and 2 are in steps 3 and 7. Figures 5 and 6 show one hop ($h = 1$) clustering with $I_c = 1$ and $I_c = 2$, respectively. Similarly, Figure 7 for $h = 2$ and $I_c = 3$ The choice for h and I_c depends on the planning. Clearly, increasing I_c reduces the number of clusters and hence the number of gateways and higher fault-tolerance. The drawback is the amount of delay.

Algorithm 2: Joint Clustering

```
Input : Transmittance Matrix $T$, $h$, $I_c \geq 1$
Output: Array $C$ of cluster heads
1 Calculate $R_h = \bigvee_{k=1}^{h} T^k$                      Eqn. 6
2 Calculate $o_{ij} = \sum_{k=1}^{N} r_{ik} \wedge r_{jk}$     Eqn. 10
  $1 \leq i, j \leq N$
3 Calculate $A$ from $O$ for a given $I_c$                      Eqn. 11
4 Calculate $A'$ from $A$
5 Use the maximal independent set [15] to identify the
  cluster heads.
6 Form clusters by incorporating the reachability set (from
  $R_h$) for each cluster head.
7 Assign nodes outsides clusters to adjacent clusters.
```

VI. PERFORMANCE

In multi-hop networks, the throughput performance of a connection decays exponentially with an increase in hop count.

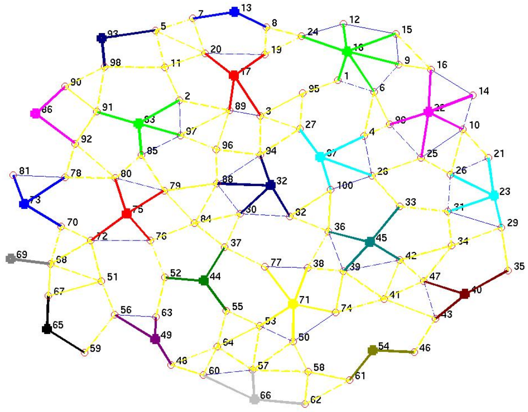


Fig. 5. $h = 1, I_c = 1$

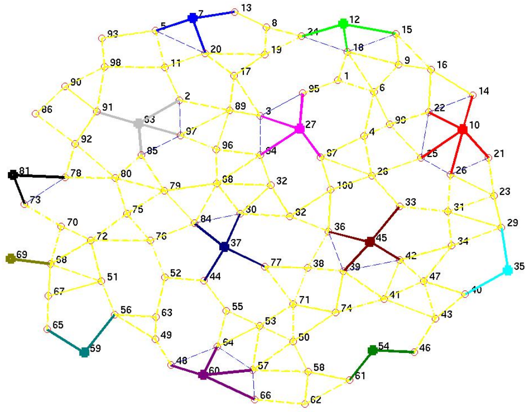


Fig. 6. $h = 1, I_c = 2$

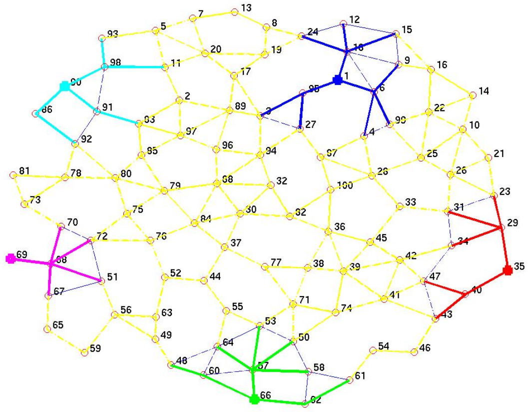


Fig. 7. $h = 2, I_c = 3$.

This is illustrated in Figure 8 for a simple network that is illustrated in Figure 9 in which a packet hops towards a gateway. A packet may runs into successive contentions and that results in higher blocking probability on each hop along the path towards its intended gateway. Each link carries a local traffic load (ρ) and relays up-stream traffic from previous nodes.

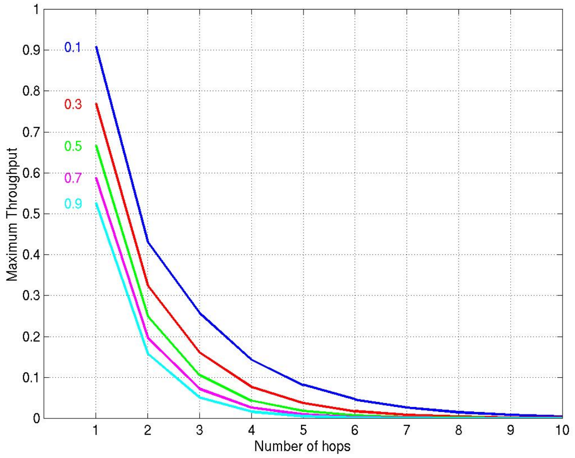


Fig. 8. Maximum throughput performance across different traffic loads.

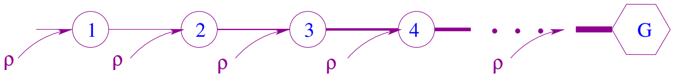


Fig. 9. A linear multi-hop network.

Figure 8 illustrates the theoretical end-to-end throughput as a function Erlang blocking probability for different traffic load (ρ) excluding loss rates. While Erlang blocking probability has been studied extensively in the content of switching networks and telephony, it can be used to approximate the blocking probably for applications such as VoIP in packet switching networks or wireless cellular systems, in which the end-to-end is connection-oriented. The exponential throughput degradation has also been observed in several experiments we conducted with Roofnet [16] which is discussed in Section VI-A, and simulation results we obtained in Section VI-B.

A. Roofnet Experiment

In our Roofnet experiment, a 5-node mesh network was created in a 3D indoor environment. The configuration of wireless network is depicted in Figure 10. With the Roofnet protocol [16] installed on each router (54 GHz, 802.11g), we measured the effect of the number of hops as well as

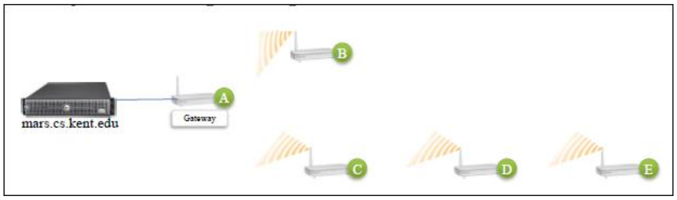


Fig. 10. A small Roofnet configuration.

the hop distance (in dB) between each pair of relay routers. File with various sizes destined towards the gateway (node A in Figure (10) were generated by the clients that are connected to a neighboring relay router. Each experiment was conducted five times at different times of the day and the results were averaged. The experiment was then repeated by increasing the hop distance. We also varied the Euclidian distance within each hop. Figure 11 illustrates the exponential decay of throughput performance when a hop distance (left) or the hop count (right) increases. The two major observation from Figure 11 are: (i) the transmission range between routers has to be factored into the clustering and deployment, as incorporated in Algorithm 1, and (ii) the throughput disparity for nodes distant away from the gateway has to be mitigated, as incorporated in Algorithm 2.

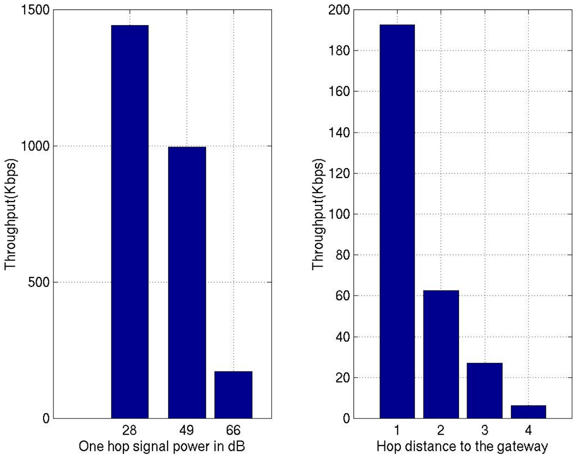


Fig. 11. The effect of hop distance (left) and hop count (right) on throughput.

B. Simulation Experiment (Qualnet)

In addition to Roofnet experiment, we also used Qualnet [17] simulator to perform two separate experiments. The first was to study the effect of hop distance on throughput and access fairness, and the second was to see the effect of providing alternate cluster membership for a source node on the edge of a cluster as proposed in this paper to increase network resilience with respect to failure.

In the first experiment, we setup five wireless nodes as a linear multi-hop network, similar to the network in Figure 9, with the first node being the traffic source and the gateway node being the traffic destination. We then increased the load, by increasing the traffic generated on the source node and observed the effect of load on the throughput. We repeated the simulation with traffic flows between source destination pairs. In this experiment, we limit the hop-counts to 4, as the throughput performance deteriorates significantly beyond 4 hops. Figure 12 shows the throughput performance varying based on the load for different hop distances. We observed that the throughput of the flows with fewer hop count is significantly better than the throughput of flows with higher hop count. As load increases beyond 40-50%, the throughput for all scenarios start decreasing, mainly due to the contention resolution and back-off algorithms provisioned in the 802.11 protocol. This result is in line with our analysis and the Roofnet experiments.

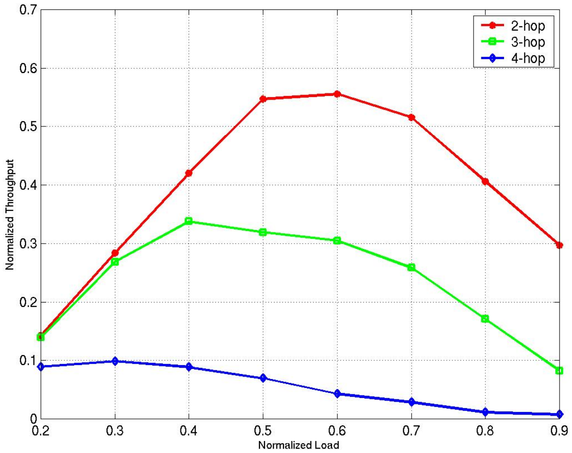


Fig. 12. Load vs. throughput with hop distance.

In the second experiment as shown in Figure 13, we allowed overlapping of clusters in the planning phase, thus enabling node S to be part of cluster C1 and C2. We created a traffic flow from node S to node D. We then studied the effect of load on the throughput with and without the overlapping clustering. Figure 14 illustrates the effect of load on the throughput with a node belongs to one or two clusters. The throughput for a node is significantly higher if it belong to two clusters.

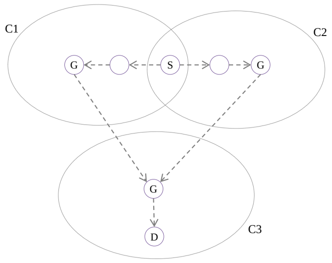


Fig. 13. Overlapping clusters simulation setup.

VII. CONCLUSION

Mesh networks, due to their multi-point to multi-point architecture, inherently lend themselves to being more resilient to faults. However, the placement of wired gateways in these WMNs has a significant impact the on network throughput performance, cost and capacity to satisfying the quality of service (QoS) requirements as well as fault tolerance. In the context of gateway placement, the QoS is influenced by the number of gateways, the number of nodes served by each gateway, the location of the gateways, and the relay load on each wireless router.

In this paper we developed a new clustering technique that improves fault-tolerance in wireless mesh networks. It

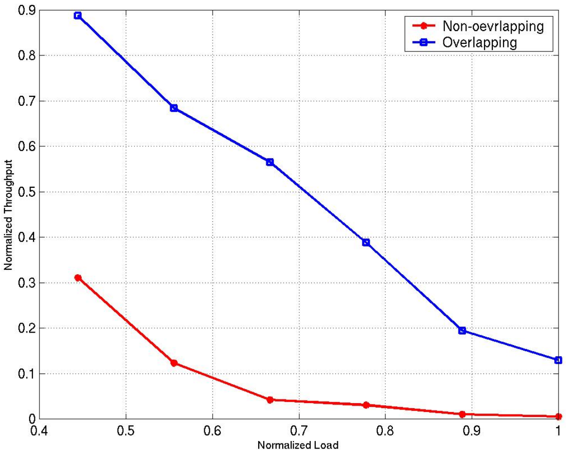


Fig. 14. Load vs. throughput with and without overlapping

also mitigates the throughput disparity among nodes distant way from a gateway by allowing them to join multi-cluster. Simulation results and measurements have shown a significant improvement in terms of throughput once clustering is incorporated during the deployment process. The clustering is independent of underlying network routing protocol, but improves the overall performance.

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