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Clustering Formation and Topology Control in Multi-Radio Multi-Channel Wireless Mesh Networks

Ma. Victoria Que* *Associate Member*, Won-Joo Hwang**° *Lifelong Member*

ABSTRACT

Convergence of various wireless systems can be cost effectively achieved through enhancement of existing technology. The emergence of Wireless Mesh Network (WMN) entails the interoperability and interconnection of various wireless technologies in one single system. Furthermore, WMN can be implemented with multi-radio and multi-channel enhancement. A multi-radio, multi-channel wireless mesh network could greatly improve certain networking performance metrics. In this research, two approaches namely, clustering and topology control mechanisms are integrated with multi-radio multi-channel wireless mesh network. A Clustering and Topology Control Algorithm (CTCA)is presented that would prolong network lifetime of the client nodes and maintain connectivity of the routers.

Key Words : Wireless mesh network, Topology control, Clustering, Multi-radio, Multi-channel

I. Introduction

Wireless mesh network (WMN) is an emerging technology in next generation wireless networks. It offers diversified capabilities that differentiate it from ad hoc networks. Two of these are the introduction of multi-radio and multi-channel capabilities on top of WMN that offers improvement on scalability. However, without the proper utilization of these advantages, its goals may not be realized. Similar to any brand new technology, WMN is currently undergoing rapid research developments and most of them are still on its infancy[1]. Generally, WMN caters numerous wireless nodes with different characteristics and it is only essential that any protocol design should consider these. There are two types of nodes in WMN: mesh clients and mesh routers. These two have contra-distinct qualities and roles in the network. Mesh clients can be highly mobile, battery-powered and have simpler hardware/software. On the other hand, mesh routers form the backbone of the network, usually not mobile, mains powered and have complex hardware that could take on multi-radio and multi-channel capabilities. With these differences, this imposes problem in organizing the nodes and maintaining operation while achieving scalability as the network grows. Figure 1 shows a hybrid model of wireless mesh network. The dotted lines symbolize wireless links and the solid lines correspond to a wired connection to the Internet.

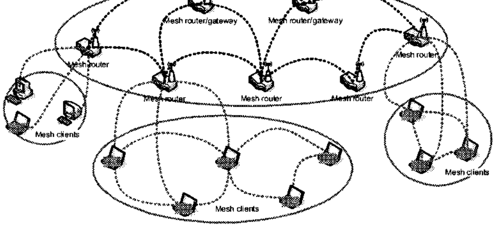

Fig. 1. A hybrid wireless mesh network composed of wireless mesh clients and mesh routers which form the backbone of the network.

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* 인제대학교 전자정보통신공학과 (tori_q81@yahoo.com)
** 인제대학교 정보통신공학과 고안전 차량 핵심기술 연구소, (ichwang@inje.ac.kr)(° : 교신저자)

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Table 1. Characteristics of Wireless Mesh Routers and Mesh Clients

	Mesh Router	Mesh Clients
Power	Main s-powered	Battery-powered
Hardware	Complex and more functionalities	Simple
Mobility	Low mobility	High mobility

Most devices in wireless networks are battery powered, resources like energy should be conserved to prolong network lifetime. Unlike in wireless sensor networks, where in all nodes are undergo an energy-saving phase, not all wireless mesh network nodes need to enter this phase. Table 1 summarizes the differences between mesh routers and clients. Identifying the differences and problems among network entities and applying the appropriate solution are the foci of this paper. Problems pertaining to mobility, power management, connectivity are addressed through exploitation of the nodes'distinct characteristics and utilization of clustering and topology control. Clustering and topology control are both techniques used in ad hoc networks and on this research, we focus on the usage of these two methods for multi-radio multi-channel wireless mesh networks.

Topology control is used in ad hoc networks especially on sensor networks to maintain connectivity and energy efficiency[2]. Through this, we would like to determine an appropriate topology control for wireless mesh network that would maintain connectivity. In addition to the aforementioned, clustering has been used in ad hoc networks too to provide the same extent of energy efficiency but with additional benefits such as hierarchical structure and mobility support[3-5], Moreover, clustering improves scalability[6], so that even if an extra node is added to the network, the network would be able to handle the change and maintain its stability. Mobility can also be one of criteria for clustering[7].

Throughout this document the word "nodes" could mean both wireless mesh routers and clients depending on the context. Mesh routers could be written interchangeably as is, "routers", "clusterhead" or "wireless mesh routers". Similarly, mesh clients would be identified as "clients", "cluster nodes", "mesh clients" or "wireless mesh clients".

This paper is organized as follows: Section II presents the related works. Section III presents the problem outline and model. Section IV and V presents the system model of multi-radio and multi-channel WMN and introduces clustering and topology control algorithm for wireless client-to-router and router-to-router communication. Section VI showcases performance evaluation of the algorithm. Examples of application scenarios are described in Section VII. Finally, Section IX concludes the paper.

Ⅱ. Related Works

2.1 Wireless Mesh Network

Wireless networks has evolved over the years, it has offered access to information withgreater coverage. The demand for wireless access has increased likewise the number of installed access points (AP)[8]. Most of these APs are connected through wired connection and as the amount of installed of APs increases, the number of wired connections become more complex and costly. Furthermore, the significant amount of time and disruptions to normal activity involved in cabling and installation made it not viable for large congested landscapes[9]. This makes headway to the growth of WMN. WMN provides wireless mesh connectivity among APs. As the 802.11 working group in IEEE(Institute of Electrical and Electronics Engineers) has been plotting on the design of 802.11s standard for mesh network, many organizations, universities and local governments are currently installing or planning to install this kind of network to provide area-wide access to the Internet or private information.

WMN offers comparable to better service in comparison to other networks[10]. Its bandwidth and coverage offered are average with very low upfront expenses.

WMN can both support mesh and ad hoc networking. It is capable of self-forming, self-healing and self-organizing making it to have a very low maintenance cost and attractive for any application scenarios. It has support for multi-hop communication on wireless mesh infrastructure.

2.2 Network Entities

There are three network entities in WMN: gateways, wireless routers and wireless clients. This paper concentrates on wireless routers and clients and the links associated between them. As Table 1 shows the differences between the nodes, Table 2 shows the differences between links.

On this paper, we have selected to a purely point-to-point or single-hop communication for client-to-router for reasons that will be discussed later on.

Table 2. The differences between communication links in WMN.

Connection Links	Name	Communication Type	Bottleneck
Client - to - Router	Access Links	Point-to-point/ Point-to-Multipoint	Not often
Router - to - Router	Backbone Links	Multipoint-to-Multipoint	Often
Router - to - Gateway	Backhaul Links	Point-to-point/ Point-to-Multipoint	Not often

2.3 Critical Factors in Design

Most of the researches concerning WMN are somehow an adaptation from wireless ad hoc networks. The primal key for an effective design is identifying the fine line that differentiates WMN from wireless ad hoc network. Table 3 shows the differences between them on several categories. Although, ad hoc network could be a subset of wireless mesh network, there are some major differences between them and it is important to identify them especially on adopting protocols that are inherently for wireless ad hoc networks.

Table 3. The differences between WMN and wireless ad hoc networks

Category	Wireless Mesh Network	Wireless Ad Hoc Network
Structure	Consists of backbone network	Individual contributions of end users
Routing	Mesh routers do the routing, hence, less load on users	Users do the routing and configuration
Multiple radio	Separation of tasks on different radio	Tasks are done on the same channel
Mobility	Dependent on node type	Dependent on movement of users

2.4 Topology Control and Clustering

The definition of topology control has evolved as researches proliferate to seek the most appropriate method. The foregoing goal of topology control is to provide an energy efficient network and it eventually grew as more protocols were developed. The nascence of topology control can be rooted from schemes that limit the number of neighbors of a node by controlling transmission power or reducing the transmit radius. [11], [12], [13] and [14] are some of the studies that discuss various ways to do transmit power adjustment. Prior to clustering, the most popular topology control protocols then were schemes that determine a set of connected representative nodes. GAF[15], Span[16], ASCENT[17] belong in this category. In GAF (Geographic Adaptive Fidelity), the network is divided into grids and designates one node as the representative for each grid cell. While in Span, certain nodes are assumed to a role of a coordinator based on connectivity criteria while other nodes are allowed to sleep and not to participate in routing. Similarly, ASCENT (Adaptive Self-Configuring sEnsor Networks Topologies) chooses which nodes are active fora given time with consideration of both connectivity and communication reliability. The emergence of clustering methods can be traced back with the introduction of two distributed algorithms: lowest-ID algorithm and highest connectivity algorithm which are discussed in detail in [18]. In these two algorithms, a clusterhead is chosen among certain group of nodes. As their names suggest, the former algorithm selects the node with the lowest ID while the latter selects the node with the highest connectivity. Although, originally, clustering have been developed for wireless ad hoc networks to provide a kind of infrastructure that would allocate resources and support multi-hop routing, its usage can be also extended to provide energy efficiency. Its energy efficiency potential has been examined by applying it to wireless sensor networks. One of the first clustering protocol is LEACH (Low Energy Adaptive Clustering Hierarchy) [19] which is based on one-hop communication which transmits aggregated data of nodes from clusterhead to base station. Another one is HEED (Hybrid, Energy-efficient, Distributed clustering approach)[20], which is unlike LEACH, uses multi-hop communication and selects clusterhead in O(1) time. Similarly, EECS (Energy Efficient Clustering Scheme) [21] performs clustering by electing clusterhead with the most residual energy.

On this paper these two methods: clustering and topology control are combined to handle the differences among network entities in wireless mesh networks. We use these two to handle connectivity and scalability of the network.

Ⅲ. Problem Outline and Model

The overall system design problem for WMN can be divided into two sub-problems. The first problem is to determine the best communication paradigm for the router-to-client links, energy constraints on the client, capabilities of the router, and the communication complexity of the whole process. The second problem is to determine a topology for router-to-router links that would ensure connectivity. These two problems will be dealt in detail on the next section.

The model involves static wireless mesh routers and mobile wireless mesh clients. Wireless mesh routers should have at least two wireless interfaces. Moreover, they are more powerful compared to the capabilities of mesh clients, in terms of available functions and hardware.

We define a graph G with size m x n with two node types V_{Cn} and $V_{Rn} \in V$ and two types of link E_{Cn} and $E_{Rn} \in E$. V_{Rn} are static, mains-powered and have Δ multi-radio interfaces and Γ multi-channel interfaces while V_{Cn} are simple and mobile. E_{Cn} is the set of all links between V_{Cn} and V_{Rn} while E_{Rn} is the set of all links that connect V_{Rns}. All V_{Rn} are said to be located evenly in G, that any V_{Cn} can find a nearby V_{Rn} to connect with. V_{Rn} has smooth movement on G, that is, if G is divided into cells, V_{Rn} cannot cross more than one cell at any instant.

For the purpose of this paper, we consider that wireless mesh routers have $\Delta = 2$ radios and the same number of channels Γ wherein one of the channels is specifically for mobility transition messages. The two types of radio available for wireless mesh routers, one is low power and the other is high power[25]. The high power radios used to communicate with another mesh router while the low power radio is used to communicate to the mesh clients. Wireless mesh routers are chosen to become clusterheads while mesh clients are the cluster nodes. We aim to formulate a general topology for WMN that would prolong network lifetime and ensure connectivity.

Graphically, wireless mesh network can be divided into parts depending on the links in between entities, as shown in Figure 2. The access links

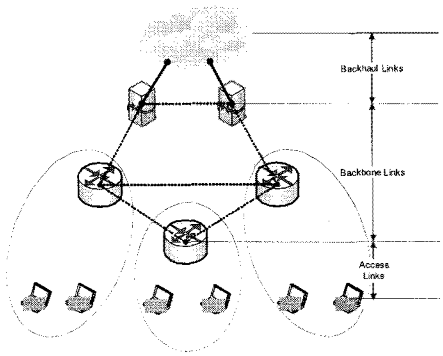


Fig. 2. Decomposed Wireless Mesh Network.

are the paths for client - to-router communication. The backbone links are the paths for router-to-gateway and router-to-router communication. Finally, backhaul links are paths for gateway-to-Internet communication. On this paper, we will only focus on the first two links as mentioned since backhaul links are often not cause of bottlenecks[10].

To arrive to the proposed algorithm, CTCA, we divided our problem into two parts: First is the mesh clients-to-mesh router communication, followed by mesh router-to-mesh client communication.

Ⅳ. Mesh Clients-to-Mesh Router Communication

As stated, we model mesh clients as mobile and battery powered, while mesh routers are not. From this, we would like to address specific problems such as:

- What communication paradigm would suit the mesh clients-to-mesh router links?
- How increasing number of nodes and energy of the mesh clients affect the topology of the access links?

4.1 Single-hop vs. Multi-hop Clustering

We consider clustering as the main topology for mesh clients-to-mesh router communication. Clustering has been the method used in wireless sensor nodes where in the cluster nodes send data to the clusterhead for aggregation[22]. In wireless mesh network context, we define that our mesh clients are the cluster nodes and the mesh routers are the clusterheads. However, we need to select which communication paradigm would suit: single-hop or multi-hop communication, given the constraints we have. We analyze each scenario and show which approach is better.

4.1.1 Single-Hop Mode

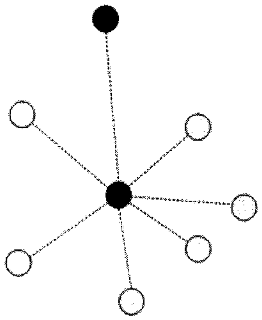


Fig. 3. Single Hop Clustering

In single-hop clustering, as shown in Figure 3, each cluster node can directly communicate with the clusterhead. Although, seemingly the cluster nodes are treated equally, one of them, the farthest of them all from the clusterhead, determines the lifetime of the cluster. This is because the farthest node will need to exert more energy to reach the clusterhead. Note that, wireless clients are the cluster nodes and therefore battery powered and energy constrained. The energy expenditure of any sending cluster node is given by (1), sum of the electronics energy and amplifier energy[19].

$$E_{\text{single-hop}} = E_{elec} + E_{amp} \tag{1}$$

where in the amplifier energy is defined as: $E_{amp}=cd^k$, where c is a constant for propagation loss and antenna gains of receiver/transceiver, d is the distance of the cluster node from the clusterhead and k is the surrounding's propagation loss constant. Therefore, the farthest node will need to have the most energy since its d is the highest. Hence, the life of a cluster is bounded by the first node to die and which, on this case is the farthest node. The required energy of the farthest node for the cluster to survive T cycles is:

$$E_{\text{single-hop*}} = T(2E_{elec} + cd^k) \tag{2}$$

In equation (2), we take note the receiving energy expenditure of a cluster node by multiplying 2 on the circuitry since only the receiving circuitry is involved in the process.

4.1.2 Multi-hop Mode

In multi-hop communication, figure 4, some cluster nodes closer to the clusterhead may need

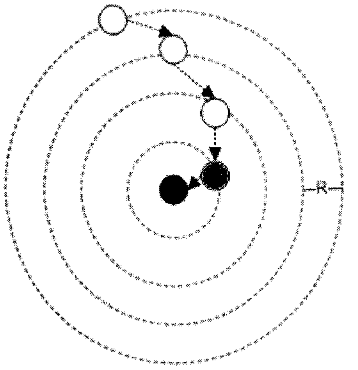


Fig. 4. **Multi-Hop Clustering**

to do additional function such as to relay data coming from nodes that are farther away. These nodes have additional functions and determinant of the lifetime of the cluster in multi-hop environment. We divide the clusterhead transmission range into concentric circles of width R. A packet in the nth ring needs to travel through the inner rings to reach the clusterhead. We say that the rings could be from 1 to d/R where $d \geq R$. If there are N nodes, a node in the nth ring will have to relay an average of p_n packets:

$$E_{\text{multi-hop}} = (2E_{elec} + E_{amp})_{self} + (2E_{elec} + E_{amp})_{relay} P_n \quad (3)$$

where, $$p_n = \frac{N(\pi d^2 - \pi(nR)^2)/\pi d^2}{N(\pi(nR)^2 - \pi((n-1)R)^2)/\pi d^2} = \frac{d^2 - n^2R^2}{R^2(2n-1)}.$$

The numerator $N(\pi d^2 - \pi(nR)^2)/\pi d^2$ constitutes the average number of nodes that lie outside the nth ring and needs the node in nth ring to relay the packets it has to send or receive. The denominator $N(\pi(nR)^2 - \pi((n-1)R)^2)/\pi d^2$is the number of nodes in the nth ring that need to relay the packet from outer rings. Aside from relaying a packet for other nodes in the cluster, a node needs to send its own packet as well. When receiving a packet only the receiver circuitry is used, so that the E_{elec} on the second term of (3) is of factor 2. Rewriting equation (3), we arrive to the $E_{multi\text{-}hop*}$ needed for the multi-hop cluster to survive T operating cycles.

$$E_{\text{multi-hop*}} = T((2E_{elec} + cR^k) + (2E_{elec} + cR^k)p_n) \quad (4)$$

Considering the worst case scenario that is n=1, the closest ring from the clusterhead, we get:

$$E_{\text{multi-hop*}} = T(2E_{elec} + cR^k) + (2E_{elec} + cR^k)(\frac{d^2}{R^2} - 1) \quad (5)$$

4.1.3 Synthesis

Now, we need to compare the two worst case scenarios of single-hop and multi-hop clustering in terms of battery energy required to ensure a lifetime of T operating cycles. We go back to equation (2) and (5):

$$E_{\text{single-hop*}} = T(2E_{elec} + cd^k)$$

$$E_{\text{multi-hop*}} = T(2E_{elec} + cR^k) + (2E_{elec} + cR^k)(\frac{d^2}{R^2} - 1).$$

Ideally, graphing the required energy to survive T cycles as one goes farther away from the clusterhead for both cases, we have something like on figure 5. This shows that as we observe nodes and considering their distance from the clusterhead, we can see difference in node survivability between single-hop clustering and multi-hop clustering.

For single-hop, it is the farthest cluster node from the clusterhead since it needs more energy to communicate with the clusterhead while on multi-hop, it is the nearest cluster node since it needs to expend more energy to relay packets for the nodes that are farther away. By inspection, it is apparent that energy requirement for single-hop is less than that of multi-hop to survive T cycles until a certain distance and is therefore more energy efficient.

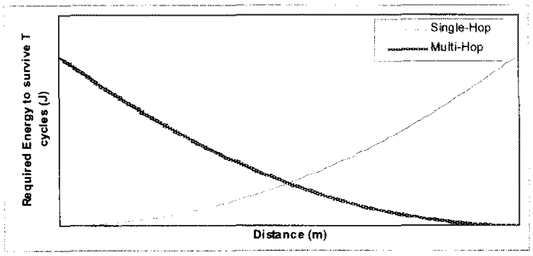


Fig. 5. Comparison of Single-Hop and Multi-Hop Clustering

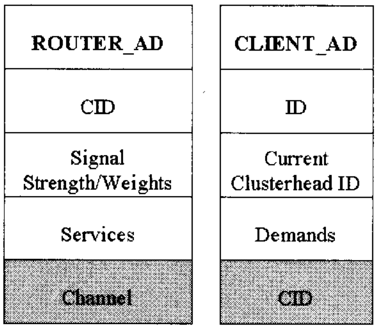
4.2 Clustering Algorithm

We introduce 2 advertisements that handle signaling in the system, namely: ROUTER_AD and CLIENT_AD.

The ROUTER_AD is propagated by the mesh routers while CLIENT_AD is propagated by the mesh clients. The information inside these advertisements is shown in figure 6. For clustering we used the ROUTER_ADs which are sent through low-power radio.

Initially, a wireless mesh client will associate with a wireless mesh router, based from a ROUTER_AD it receives. A wireless mesh client will initiate an association request with a router based on the signal strength and services it offers which can be referred as weights as indicated in the ROUTER_AD. The clustering algorithm starts with wireless mesh routers. The wireless mesh routers will disseminate this beacon like messages using both its low power and high power radio. If another wireless mesh router received this message on its high power radio, it will forward the message to its own active clusternodes for reasons that will be discussed later on. If an unassociated wireless client received this, it will associate to that router and become a clusternode. After this phase, clusters are formed with mesh router as clusterhead and mesh client as a cluster node. Figure 7 describes this mechanism.

A cluster node should need to know the capability of the new clusterhead and if it allows additional connection and provides the service it needs. The router will broadcast its ROUTER_AD over specific channel among its cluster and to the nodes in the neighboring clusters, every time t_n while the client needs to advertise its own every t_n.



ROUTER_AD	CLIENT_AD
CID	ID
Signal Strength/Weights	Current Clusterhead ID
Services	Demands
Channel	CID

Fig. 6. ROUTER_AD and CLIENT_AD message format.

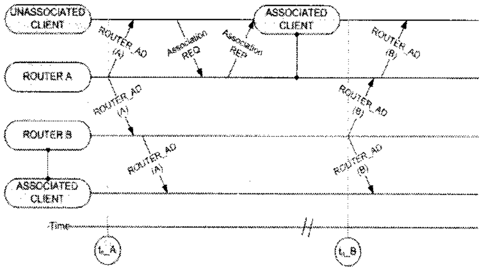


Fig. 7. The proposed clustering algorithm

V. Mesh Router-to-Mesh Router Communication

The wireless mesh routers can have multiple radios and multiple channels[1]. Although, at first look, it could be an advantage, it still needs appropriate planning to be effective and exploit its advantages. Compared to any other links, the links between mesh routers can usually be a source of bottle neck[10].

We model our wireless mesh routers as nodes that have no power constraints and have multiple interfaces and dual radios. For simplicity of synthesis, there are at most two radios per router. One radio which is the low-power radio is especially for client-to-router communications while the other which is the high-power radio is for router-to-router communications. Figure 8 shows a 2-radio model wireless mesh framework.

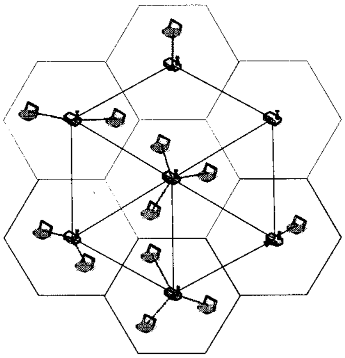


Fig. 8. Two-radio wireless mesh router system

Even though, wireless mesh routers have two interfaces the router-to-router topology problem can be simplified to become a channel assignment problem simply because, only one radio/interface is designated for router-to-router communication.

In this section, we will only consider the wireless mesh routers and the links between them. We have a graph G with entities (V,E) where node $v \in V$ and link $e \in E$. For every pair that of (x,v) $\in V$. If a physical communication link exists between them, we denote it by e_{xv} where $e_{xv} \in E$. Also, this link is said to be bidirectional so that $e_{xv} = e_{vx}$ $\forall x,\ v \in V,\ e_{xv} \in E$. Therefore, in general any link e_{xv} can have values:

$$e_{xv} = \begin{cases} 0, e_{xv} \notin E \\ 1, e_{xv} \in E \end{cases} \qquad \forall x,\ v \in V \tag{6}$$

The router as modeled could only have 1 network interface for router-to-router communication so that its number of connections is limited to the maximum possible channels available, Γ.

$$\sum_{k \in V, x \neq k, e_{xk} \in E} e_{xk} \leq \Gamma \quad , \qquad \sum_{k \in V, v \neq k, e_{vk} \in E} e_{vk} \leq \Gamma \tag{7}$$

From [23], ripple effect can be prevented by assigning one node or interface in the link that will do the channel allocation. So that if x assigns a channel to be used by link e_{xv}, the same channel cannot be used by v to attach to other node. We denote δ_{xv} to be the indicator of it.

$$\delta_{xv} = \begin{cases} 1, & \text{if node } x \text{ is responsible for channel assignment} \\ 0, & \text{otherwise} \end{cases} \tag{8}$$

If link e_{xv} exists,

$$\delta_{xv} + \delta_{vx} = e_{xv} \tag{9}$$

(9) denotes that only one of the terms can have a value of 1 and the other being 0 based from (16). From [23], if e_{xv} is a link used by source s and destination d to route packets, it is denoted by:

$$\alpha_{xv}^{sd} = \begin{cases} 1, & \text{if the traffic from s to d is routed through } e_{xv} \\ 0, & \text{otherwise} \end{cases} \tag{10}$$

where, $\forall x,\ v,\ s,\ d \in V,\ e_{xv} \in E$.

A source to destination pair should have constraint on the number of hops it should take

$$\sum_{x,v \in V, e_{xv} \in E} \alpha_{xv}^{sd} \leq H^{sd} \qquad \forall\ s,d \in V \tag{11}$$

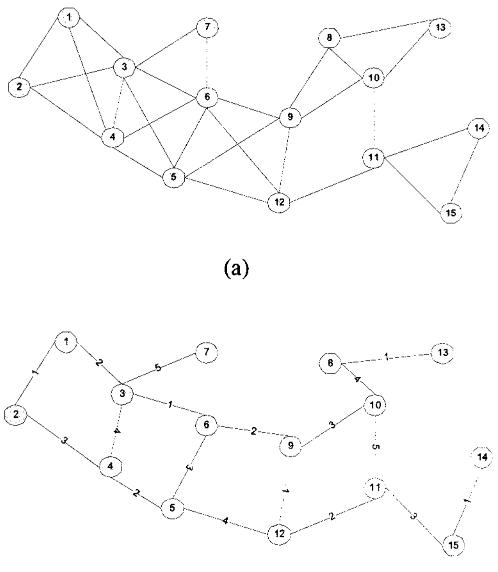
The algorithm that solves the following constraints above gives out a logical topology design for backbone links.

The channel on ROUTER_AD lists the free channels of the router that can be used for association. If an unassociated router received this advertisement, it associates using the channel enforced by the ROUTER_AD. If the router who received the ROUTER_AD is already associated, it checks if it has a free channel indicated by the ROUTER_AD, it associates if they have the same free channel and not if it does not have and forwards the ROUTER_AD to its own clients within its clusters. The algorithm is shown below:

```
BACKBONE   PROCEDURE
For ROUTER_AD received from Y
{
   If (ROUTER X and Unassociated)
   {
    $e_{YX} = 1$
   }
   If (ROUTER X and Associated)
   {
    if (X.free_channel = Y.channel)
    {
      $e_{YX} = 1$
      send ROUTER_AD to x.client
    }
    else
    {
      send ROUTER_AD to x.client
    }
   }
}
```

Fig. 9. Backbone Topology Building Procedure

In the algorithm that it is easy to see that the number of connections that a node x is upper bounded by the number of available channels. Figure 10 shows a physical topology where in each link represents a path from source and destination Figure 10a. We set our nodes to have a maximum $\Gamma = 5$ channels per node and $H_{sd} = 2$ hops per source to destination pair. The resulting topology is shown in Figure 10b. The number on the links is the assigned channel.



(a)

(b)

Fig. 10. The physical (a) and resulting topology (b) after backbone topology formation procedure.

Ⅵ. CTCA - Clustering and Topology Control Algorithm

In this section, we present the Clustering and Topology Control Algorithm (CTCA). The overall algorithm is shown in below. This is composed of the two main catalysts: sending the ROUTER_AD and CLIENT_AD in the network. Basically, these two signaling messages trigger the overall events in the network. The router first sends a ROUTER_AD message. In searching for other routers to attach to in the backbone, the ROUTER_AD is sent to the high power radio interface. This would initiate the backbone formation procedure. For the joining of clients, the ROUTER_AD is sent through the low power radio which initiates the cluster formation procedure. It may initiate association between routers, between routers and clients and handoff procedures. This mechanism is shown in Figure 11.

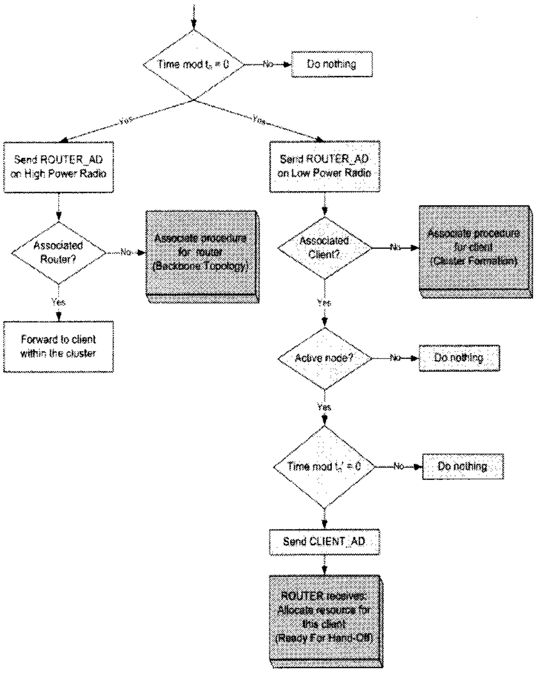


Fig. 11. The Clustering and Topology Control Algorithm (CTCA)

The CTCA is a clustering and topology control algorithm for multi-radio and multi-channel wireless mesh network. The goals as mentioned are to prolong network lifetime and maintain connectivity of the whole network with consideration of mobility, differences among nodes and lesser control overhead. To prolong the network lifetime, we utilize a single-hop communication paradigm. To maintain connectivity, a topology control algorithm is used. The formation of clustering and topology control is restricted by a control message which is employed carefully to achieve the main goals and handle the considerations.

Ⅶ. Performance Analysis

We evaluate our clustering algorithm on the access layer (wireless client-to-wireless router) communication by illustrating a series of scenarios. The analyses that will be presented will prove that CTCA's single-hop cluster formation of the access layer is scalable and prolongs network lifetime compared to multi-hop cluster formation.

Equations (2) and (5) show the required energy for the worst-case scenario of single-hop and multi-hop cluster cases, respectively. Given that T = 100 cycles, E_{elec} = $5x10^{-6}$, c = $5x10^{-6}$, and d varies within {1 - 200} meters, we have the following graph as shown in Figure 12 for different cases of k = {2, 5} with R = 100. Note that $k$is the propagation constant and is therefore dependent on the environment.

In CTCA, we add RSSI (received signal strength indicator) as one of the criteria for cluster node association. This RSSI determines how far a node from a clusterhead[24]. For the scenario above, we determine that the maximum distance is up to 100 meters for the good operation of single-hop method. We let CTCA to operate restrictedly. Using a threshold RSSI value, a cluster node discards ROUTER_IDs from clusterheads outside the operating region.

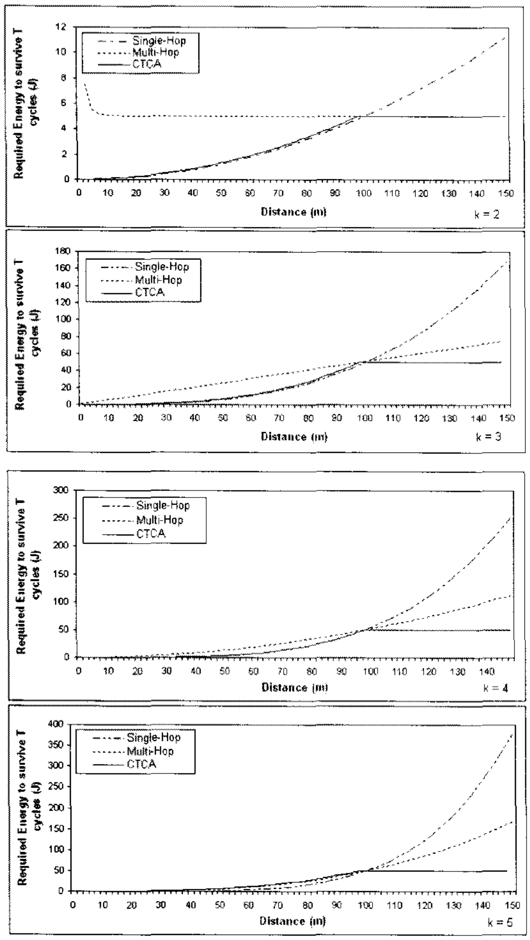


Fig. 12. The relationship of the required energy of a node to survive in T cycles and distance using CTCA, single-hop and multi-hop cluster formation with varying values of k

The distance of every client that will associate from a clusterhead should be controlled. This is because that we cannot have an arbitrary node associate with a clusterhead if it lies too far from it. Take note that, the received signal deteriorates with a factor of $1/R^k$. To prevent excessive energy expenditure, the algorithm make used of the RSSI (received signal strength indicator) and other weights in choosing router to connect to. This will control the amount of nodes and the distance. RSSI is determined by the client and it is just added in the ROUTER_AD for clarity of criteria. Another way, to prolong network lifetime is the addition of relay station. Relay station extends the coverage of a clusterhead and thus the distance of every node from a clusterhead is shortened. This relay nodes, figure 13, act like repeaters that would shorten the logical distance between the clusterhead and clusternodes. Relay nodes are not battery powered and therefore not a source of energy problem. Although this solution could be very promising, this has not been fully investigated.

To prove the scalability, we need to show that for increasing number of nodes, the CTCA single-shop should always have less amount of energy spent compared to multi-hop approach. We perform a simple simulation where in the initial energy is 100J, the transmit energy is 0.6J and receiver energy is 0.2J. We added nodes until the

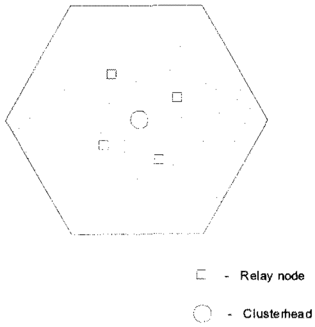


Fig. 13. Cluster using relay nodes

worst case node's energy of either case gets depleted completely. The result is shown in Figure 14 and 15 wherein for all cases, the energy spent of the single-hop and CTCA maintains to be lower than that of the multi-hop cluster.

Generally, we want to prolong the network lifetime of the cluster. In reality, the number of packets p_n need to relay by a node increases as the number of nodes in a cluster increases. In Figure 15, we plot the normalized network lifetime versus the number of nodes in the cluster. In here, the energy is fixed for both the single-hop and multi-hop initially and their distance from the clusternode is also fixed. As the number of nodes increases between the closest node and farthest node, the energy in the worst-case node in multi-hop depletes and therefore, the network lifetime decreases. However, the farthest node is the determinant for single-hop and CTCA and in figure 15, it is independent of the number of nodes in the network. From this, we show that our choice of communication in the cluster is scalable since the network lifetime is not affected by an increasing number of nodes.

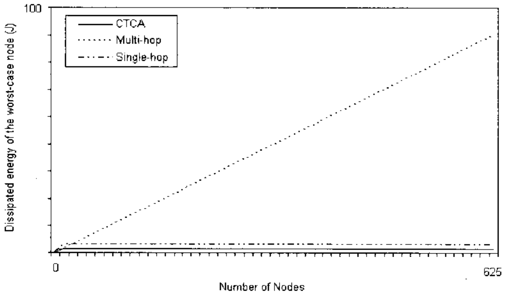


Fig. 14. The energy spent of the worst-case node and number of nodes

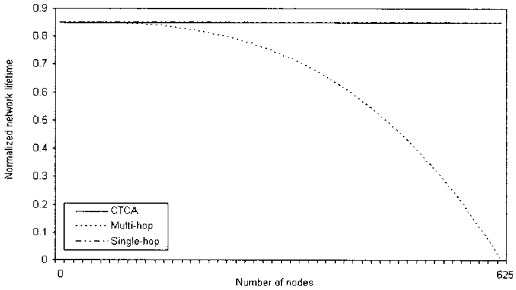


Fig. 15. Network lifetime and number of nodes

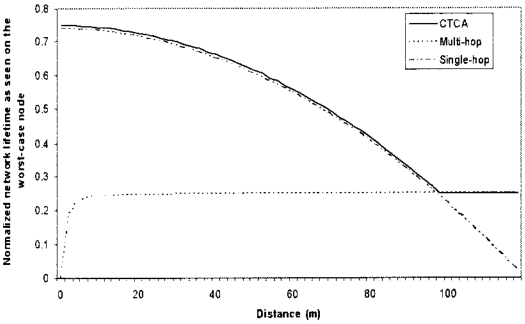


Fig. 16. The relationship of normalized network lifetime and distance.

Finally, in Figure 16, we show the relationship of distance of the worst case node to network lifetime. On single-hop, as the node goes farther away from the clusterhead, more energy is used to reach the clusterhead and this reduces cluster lifetime. On the other hand, more energy is used whenever a node is closer to the clusterhead in multi-hop cluster. Plotting the worst-case scenario for both communication models, the single-hop still wins over multi-hop in prolonging the clustered network lifetime.

Since, the communication with client-to-router and router-to-router is using different radios; these two mechanisms can be done simultaneously. This saves time and initial start ups in the network. The messages are sent via different radios and this reduces traffic for each. Following this, we would like to prove some claims in our paper.

Lemma 1: All wireless mesh clients can find a mesh router to associate with to form cluster.

Proof: Since the all the nodes are uniformly distributed throughout the network, a mesh client would surely be associated after it has received a ROUTER_ID and followed an associate procedure. Given a mesh router R_l on a space G of arbitrary size s, there exists another mesh router R_l within a transmission range T_C in a uniformly distributed space, such that a mesh client can hear a ROUTER_ID.

Lemma 2: Here exists at most one mesh router in the vicinity of a mesh client that can be associated with.

Proof: We denote R as the set of all mesh routers and R' is the set of mesh routers that have the highest signal strength P_R or highest weight within a mesh client's transmission range T_C where $\forall R_n \in R'$, $R_n'' = \{R_x | d(R_x,R_n) \le T_C, R_x \in R\}$. We also define $R_x \in R_n''$ belongs to R' which is a contradiction of the Lemma. Based on the algorithm, $R_n.P_R > R_y.P_R$, $\forall R_y \in R_n''$. Since $R_x \in R_n''$, then $R_n \cdot P_R > R_x.P_R$. If R_x belongs to R', then $R_x.P_R > R_y.P_R$ which is a contradiction. Therefore, if $R_n \in R'$ and $R_x \in R_n''$, the statement $R_x \in R'$ is false.

Ⅷ. APPLICATION

The topology set-up presented for multi-radio multi-channel wireless mesh network can be applied to several real life scenarios.

8.1 Scenario 1

We could think of the mobile mesh clients as sensor nodes while the mesh routers are the sinks. These sensor nodes are attached to children to monitor their location. An alert will be asserted whenever a child goes out of the coverage area.

8.2 Scenario 2

In a smart home, with wireless mesh routers mounted, the sensors/wireless mesh clients are scattered around to provide information regarding the physical/psychological state without intervening one's privacy.

8.3 Scenario 3

In an office, the wireless mesh routers can be mounted to every department room where every employee's computer is connected. To be able to communicate to other departments, their router will seamlessly send/receive data from other routers of another department.

Ⅸ. Conclusion

On this paper, we have formulated a clustering and topology control algorithm for multi-radio multi-channel wireless mesh networks. We divided the WMN system into two parts. The first part is called the access layer which consists of wireless mesh clients and routers and the links between them. The second part is called the backbone layer which consists of wireless mesh routers and the links between them. We use clustering and based it from single-hop communication paradigm to the access layer to prolong network lifetime and handle mobility of nodes. A topology control problem is presented for the backbone layer. We propose a heuristic which aims an overall improvement on network lifetime and sets up a topology for backbone links. A performance evaluation is provided to show the effectiveness of the proposed algorithm.

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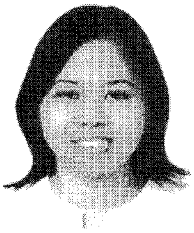
마 빅토리아 께 (Ma. Victoria Que) 준회원

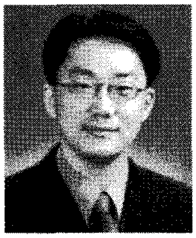


2003년 11월 Univ. of the Philippines-Diliman 컴퓨터공학과 학사

2008년 2월 인제대학교 전자정보통신공학과 석사

<관심분야> 무선 센서 네트워크, Ad hoc 네트워크, Cross-Layer 설계

황 원 주 (Won-Joo Hwang) 종신회원



1998년 2월 부산대학교 컴퓨터공학과 학사

2000년 2월 부산대학교 컴퓨터공학과 석사

2002년 9월 일본오사카대학 정보시스템공학과 박사

2002년 9월~현재 인제대학교 정보통신공학과 조교수

<관심분야> 홈 네트워크, 무선 센서 네트워크, 인터넷 QoS, 통신 최적화 이론