Enhanced Topolgoy Formation Protocol for IEEE 802.11 WLAN based Mesh Networks*

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***Abstract*—This paper deals with the topology formation schemes in the IEEE 802.11 based wireless mesh network. The recent standardization effort for specifying a wireless distribution system based on wireless mesh networking, namely the IEEE 802.11s Task Group, has proposed the "Simple Channel Unification Protocol" that coalesce all nodes into to a single channel. We show that protocols as such without exposition of the topological information may take more time to converge and have higher message overhead. We propose an enhancement of the existing protocol to reduce message and time required to generate a single unified graph in WLAN-based mesh networks. We performed simulations using the network simulator, *ns-2* and compared with the existing solution. The preliminary results show that our scheme performs better in terms of the message overhead as well as the convergence time.**

Keywords-WLAN mesh; IEEE 802.11s; channel assignment; topology formation

I. INTRODUCTION

The IEEE 802.11 family of standards [1] is currently the most popular wireless networking standards for wireless LAN. Although the existing standards provide specifications of the medium access control (MAC) and the air-interface (PHY) for connectivity among end-user stations and access points (APs), their limitations become apparent when large number of APs have no direct connection to the wired infrastructure. To overcome these limitations, wireless multi-hop mesh networking techniques are now being applied for creating wireless infrastructure backbone. In this context, the IEEE 802.11 formed the "s" task group for extending the legacy standard to provide layer-2 infrastructure meshing in the wireless LAN environment.

The objective of the IEEE 802.11s (ESS) mesh project is to develop a specification of the MAC and PHY layers for constructing a wireless distribution system (WDS), which shall function as the backbone infrastructure to the end-user devices (i.e., stations). The wireless backbone (equivalently called mesh or WLAN mesh) is formed by the collection of devices and wireless links for accessing the network services. It consists of APs (that serves stations in the basic service set) and mesh points (MPs) (nodes that forward traffic across the mesh). AP and MP can coexist in the same node, referred to as a mesh access point (MAP). Since other functional differences between MP, AP and MAP are not relevant here, we shall refer all such devices as an MP. The key requirements of WLAN mesh are to provide high-throughput gateways to the Internet access, to decrease the investment cost while setting up network, and to make its deployment simpler and easier. Therefore, one of the main focuses in the IEEE 802.11s group is on developing a self-configuring network, capable of automatic channel assignment to the one or more available interface(s). Such strategy induces the association among MPs forming a mesh topology. In this paper, we study the topology formation by assigning common channels on the neighboring MPs to enable mesh connectivity in the WLAN.

The basic protocol for the topology formation of wireless LAN Mesh in the current IEEE 802.11s draft specification [2] is called the *simple channel unification protocol (SCUP).* The SCUP assigns a common channel to the set of MPs that converges to form a unified channel graph (UCG). UCG is defined as a subset of MPs in a WLAN mesh whose interfaces are assigned a common channel. A single WLAN mesh might contain more than one joint or disjoint UCG and an MP with multiple interfaces can be the element of more than one UCGs. The SCUP runs in each MP when it is deployed and discovered by the WLAN mesh for the first time. Channels are assigned statically to each MPs for a long period of time, unless it is required to change due to the change in topology or other regulatory requirements. The so-called *mesh channel cluster switching technique (CCST)* compliments the SCUP to maintain the WLAN topology. The CCST links a newly discovered MP into a WLAN mesh by joining it with one of the existing UCGs. Even though the current draft [2] still opens the possibility of the concurrent use of different channels in a WLAN mesh, the SCUP is so far defined to merge all connected MPs into one common channel.

A few papers [3, 4] have proposed the topology formation protocols in IEEE 802.11 based wireless mesh network. The reference [3] presents a novel formulation of the base channel assignment to ease coordination and generate topology. Similar work on channel assignment for the IEEE 802.11 two-radio mesh networks has been proposed in [4]. They propose a channel selection algorithm that chooses a channel based on the current energy level of the available multiple channels and multiple interfaces for increasing the network capacity. These protocols require mandatory presence of the nodes with multiple interfaces and do not consider the issue of backward compatibility.

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In the IEEE 802.11s, one of the motivations to construct a unified channel WLAN mesh is to let the legacy stations to co-exist and interoperate using the legacy protocols. Moreover, further advancement to include other protocols on top of such topology is expected to be easily implemented. For example, the dynamic channel assignment protocol, named the multi-channel MAC (MMAC) [2] can execute on top of the established topology.

Both SCUP and CCST can operate with the MPs built with single or multiple-interfaces. Despite the operational requirements are satisfied by the SCUP and CCST, their performances lack efficiency. SCUP depends upon a simple heuristic called a channel precedence indicator (CPI) that is computed as a sum of a random number and the time spent by an MP in the WLAN mesh. We show that the SCUP along with the CCST incurs high message overhead and require significant time for forming a WLAN mesh topology. Due to this reason, the amount of network resource can be held during the initialization and the maintenance of the network. In this paper, we discuss the cause of this problem and propose an enhancement on SCUP. We exploit the topology information, i.e., the size of the emerging UCG to reduce both time and the message overhead while forming the topology of a WLAN mesh. We evaluated our scheme using ns-2 simulator and compared it with SCUP of IEEE 802.11s.

In the next section, we shall provide the description about the operation of SCUP and CCST along with an illustration of a problem. We shall describe our enhancement on SCUP in section III, performance evaluation in section IV followed by the conclusion in section V.

II. THE MESH TOPOLOGY FORMING PROTOCOL IN THE IEEE 802.11S

WLAN mesh network topologies include MPs with one or more radio interfaces and may utilize multiple channels bounded by the network and device capability. For example, three orthogonal channels are at most available in the IEEE 802.11b radio [1]. Each interface in a WLAN mesh is assigned a unique MAC address and is treated as a unique entity even if the multiple interfaces belong to the same MP. However, in this paper, we consider only single interface MPs that initially assigns a randomly selected channel.

MPs in the IEEE 802.11s network shall have two channel selection modes for enabling topology. A default mode shall be a simple channel unification mode, in which SCUP is executed for a mesh topology formation. Another mode, called the advanced channel assignment mode is not specified in the draft specification [2], hence is open for vendors to implement specific protocols and might vary depending upon several factors. The mode of operation is advertised periodically through the beacons and probe request/response frames during the neighbor discovery. It should be noted that in a single WLAN mesh all MPs must be operating under a common mode for successful operation and interoperability. The operations of SCUP and CCST are further described in detail.

A. Simple Channel Unification Protocol (SCUP)

All MPs shall set SCUP mode *ON* for running this protocol. A neighbor discovery protocol is enabled by sending beacons and probe request/response frames. A *passive approach* that uses beacons result in longer response time because an MP has to listen to all channels, whereas an *active approach* uses probe request/response frames and result in faster topology generation, however with the penalty of additional frames [5]. After this phase, MPs will form the mesh network by associating with the neighboring nodes.

The process of neighbor discovery and association requires MPs to assign channels to their own interface such that the connectivity is established. If an MP is unable to detect any neighbor, it randomly selects one channel and assigns itself a CPI. The problem of which channel to assign among a set of available channels is left open for the vendors, which might depend upon the channel quality estimation or other techniques. The CPI is used as an indicator to select a common channel while two disjoint meshes detect each other in a WLAN mesh. When the neighboring MPs span more than one channel, it shall select the channel of the MP with the numerically highest CPI value. If the identified unification channel is different than the current operating channel of the MP, an MP with a smaller CPI shall switch the channel by invoking the CCST protocol as described in the following subsection.

B. Cluster Channel Switch Protocol (CCST)

The MP that needs to switch the channel first set a *switch wait timer* and then sends a *switch announcement frame* to each peer MP that is in the unified channel graph. Any MP is considered as a peer if the neighbor has a capability to associate with that MP. The peer capability is the maximum number of neighbor MPs with whom an MP can form an association. The switch wait timer is set to the number of time units by the MP that sends switch announcement frame [2]. For this, it sets a local timer and sets the new channel as a candidate channel, which shall later be assigned as an operating channel.

Each MP receiving the switch announcement frame similarly sets a local timer, copies the CPI and other required values, and further transmits the switch announcement frames to the other peers. It is possible that an MP might receive more than one switch announcement frames. In such a case, it only acts upon the frame if the CPI is larger than the CPI value of any previously received announcement frames. In case when the frames have the CPI with equal value, the tie is resolved by comparing the source address of the previously received frames. Note that when the switch wait timer is active, a MP does not originate a new announcement frame during that period. When it expires, MPs shall assign their radio interface to the candidate channel associated with the highest CPI among the neighbors. The candidate CPI is copied and used as the CPI of the MP here after. Since a common channel is systematically assigned, this protocol eventually merges all MPs into one unified channel graph. Regardless of whether the node has multiple or single interface all interfaces shall be assigned a same channel.

C. Problem Description

The SCUP assigns a common channel to all the neighboring MPs based on a CPI value computed in each MP for forming the UCG. Since CPI is the sum of a random number and the time spent after MP is powered on, it is not oriented with the topological information. Any MP can have higher CPI compared to another which can lead to the convergence of WLAN mesh based on that MP. It may not be desirable when a disjoint mesh containing large number of MPs have to switch their channels compared to another one with few MPs. This non-determinism might thus degrade the performance of the protocol.

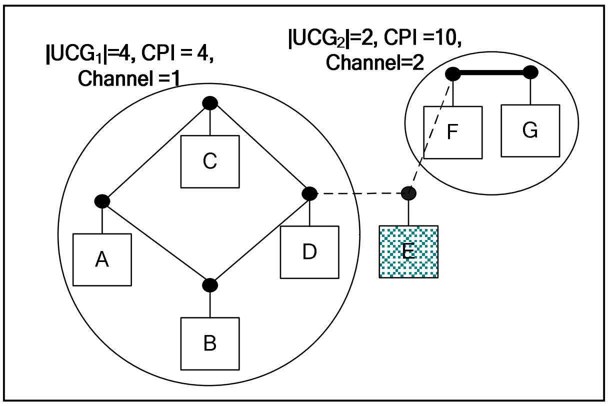

Figure 1. MPs in IEEE 802.11s WLAN with two UCGs: UCG_1 and UCG_2 being merged into one due to a newly deployed MP E

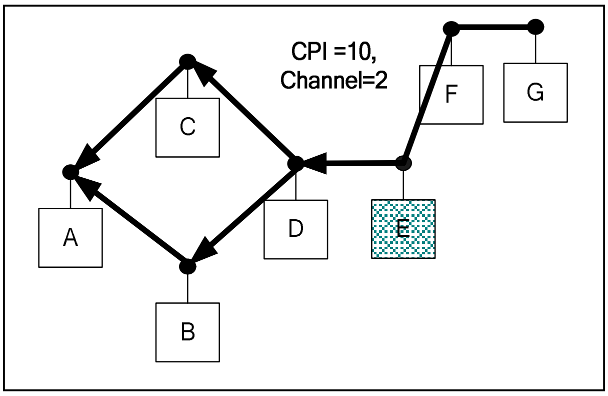

Figure 2. MP E merges to UCG_2 and sends a switch announcement frame (shown by arrowhead) to UCG_1 in SCUP, finally forming a single UCG with channel 2

Figure 1 and 2 depict the problem of message and time overhead in the SCUP and CCST. Initially in Figure 1, there exist two disjoint UCGs: UCG_1 that includes MPs A, B, C and D, and UCG_2 that includes MPs F and G. Introducing a new MP E will later connect the two disjoint meshes into one. With SCUP, MP E sets its channel according to the UCG_2 because of its higher CPI value and initiates CCST to merge both meshes into one UCG. As shown in Figure 2, the switch wait timer is started by MP E, and the switch announcement frame is transmitted to MP D, which further propagates the frames to all MPs of the UCG_1. Clearly, it requires at least extra four switch announcement frames and additional time compared to two frames if UCG_2 is requested to switch its channel. Further, this might repeatedly occur in presence of newly discovered meshes or MPs with higher CPI value. Thus, the bound on the message and the time overhead is not restricted for unifying the MPs into one UCG.

We propose to use additional topological information to form a topology more efficiently. In our scheme, we choose the size of UCG denoted by |UCG|, defined as the number of MPs associated in the given UCG. While many other parameters can be chosen, we use this information because it is easily obtained during the neighbor discovery mechanism through beacons and/or probe request/response frames. By doing so, we retain the simplicity of the protocol and also obtain the extra efficiency in terms of time and message overhead to generate a topology.

III. THE PROPOSED SCHEME

We focus on constructing the topology by merging multiple UCGs based on easily available topological information. A single unified graph is formed, with all MPs assigned to one common channel (except when the WLAN mesh contains some disjoint unreachable UCGs). The proposed scheme for an efficient topology formation maintains connectivity of MPs with all reachable neighbors and assumes that the links between MPs are bidirectional. We also assume that at least one interface for each MP is available for constructing the WLAN mesh infrastructure that does not interfere with the existing BSS traffic. Therefore, in our scheme we do not consider the legacy IEEE 802.11 network requirements. We have earlier shown that the SCUP combined with the CCST algorithm depends only on the CPI, therefore might take more time and increase the message overhead for the successful coalescing of the channels. In order to reduce these overheads and to systematically build a connected topology, we propose a simple heuristic based on the size of emerging UCG as well as CPI values.

As described earlier, a booting MP performs a neighbor discovery either through an active or passive scanning according to the draft specification [2]. For simulation, we implemented the passive mechanism by periodically sending beacons from the MPs in the WLAN mesh. A beacon message is summarized here as a tuple {*meshId*, *ucgId*, |UCG|, CPI}. *meshId* is a unique value that represents a complete WLAN mesh. Since multiple WLAN meshes can be collocated, it distinguishes one mesh from another. *ucgId* is unique to each UCGs within a single mesh. Two different UCGs assigned to the same channel might exist if they are separated by another UCG with a different channel. Since our scheme joins existing UCGs, it finally derives the topology for the entire mesh represented by one *ucgId*. As defined earlier, |UCG| denotes the size of a UCG. The value of the CPI is computed according to [2]. Similarly, a switch announcement frame is described by the following tuple, {candidate channel, |UCG|, *meshId, ucgId, CPI.*} Candidate channel is the one to which a sender MP is expected to switch. Other parameters in this frame share similar content as in the beacon frames.

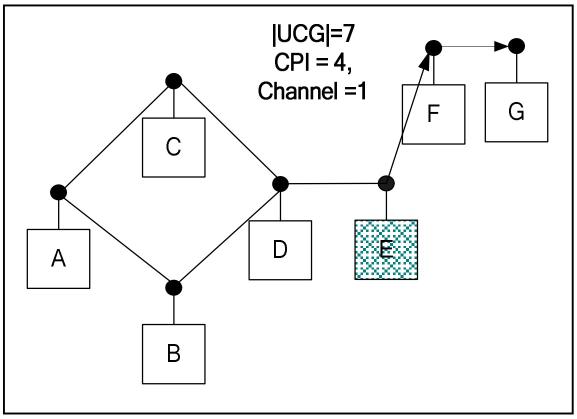

Figure 3. MP E merges to UCG_1 and sends a switch announcement frame (shown by arrowhead) to MPs in UCG_2 in the proposed scheme forming UCG with channel 1

In [2], there are several other fields of the management messages such as beacons, probe request/response, switch announcement frames, etc., but for simplicity we discuss only those fields used by our protocol. Note that the *ucgId* and |*UCG*| used by our scheme are not a part of the current IEEE 802.11s management frames. However, its implementation can be easily done by making small modification of the management frames. In our implementation, these parameters are embedded in the beacons and switch announcement frames. Each MP locally determines its channel based on the one-hop parameter received via beacons. If an MP does not receive any beacons for some time, it shall adopt its own *meshid*, assign the |UCG| value to one, randomly assign one channel and the corresponding CPI to its interface. All MPs periodically transmit and scan for beacons from the neighbor MPs.

A new MP that successfully scan an existing WLAN mesh maintains a data structure called the *neighborTable* that includes the elements from the received beacon. It first verifies that the *meshId* of the neighboring MP belongs to the same WLAN mesh and discard the ones that do not match with its profile. An MP shall check all neighbors in its *neighborTable* and choose a neighbor with the maximum |UCG| value and a different *ucgId* to merge with. If the neighbor's size is greater, an MP should switch a channel equal to that of the neighbor's channel. Thus, the MP with the smaller |UCG| value updates the new unification channel of a neighbor as the candidate channel. Further, it initiates the CCST protocol for systematically converting the operating channel of the other reachable MPs in its UCG.

If it discovers a neighbor with a higher |UCG| value but having a same *ucgId*, than it shall update the UCG size to a higher value, however does not need to transmit switch announcement frames. In case if the neighboring MPs have same |UCG|, then the CPI is be used to indicate the common channel for breaking a tie as in the SCUP protocol.

The switch announcement frame shall be transmitted by the MP according to the CCST protocol. MPs receiving this frame again compare the *ucgId* and |*UCG*|, set the switch wait timer and then finally assign a unification channel on its interfaces after the timer expires. The |UCG| monotonically increases as a new MP joins the unified channel graph. It is propagated through the periodically transmitted beacon and is updated by all MPs. Note that updating |UCG| according to its *ucgId* does not require any extra frames.

We explain the operation of our scheme with Figure 3. We have previously explained the problem of SCUP caused by the fact that MP E sends a switch announcement frame to UCG_1 containing MPs A, B, C and D. Now, instead of switching channel based on CPI, MP E that receives beacons from both MP D and MP F, select a channel based on the higher |UCG| of MP D. Before assigning the candidate channel to its interface, MP E sets a switch wait timer as in [2] and sends a switch announcement frame to MP F for unifying all MPs to channel 1. In turn, MP F shall again set its timer and send the switch announcement frame to MP G. When the timer expires, each MP switches the channel according to UCG_1, merging all nodes into a single unified channel graph. The |UCG| is now set to 5 in MP F. This value is periodically updated in all MPs in the merged UCG as it monotonically increases to higher values bounding to maximum number of MPs in the WLAN mesh. That is, every time a new MP discovers the WLAN mesh and wishes to associate, the size of existing UCG dominates the size of a single MP. In other scenario where two disjoint meshes are merged, CCST is invoked on the MPs that belong to the smaller sized UCG.

IV. PERFORMANCE ANALYSIS

We performed preliminary simulation studies using *ns-2* to evaluate our scheme. Comparison is performed with the existing scheme SCUP. Since the IEEE 802.11s protocols are not available in the simulator, we implemented both SCUP and our proposed scheme on the link layer. For evaluation we counted the number of switch announcement frames transmitted by each node to compute the message overhead. Beacons and other management messages such as peer request/response frames are equivalent in both protocols. The convergence time is defined as the time when all MPs switch to a same channel. It is estimated as a simulation time when all MPs are unified and no further channel switching is performed.

For our simulation environment we created a topology of 1000x1000 sq. m and randomly deployed 10, 15, 20, 25 and 30 nodes. The IEEE 802.11s requirement document recommends 32 forwarding APs (MPs) in a single WLAN mesh [6]. All nodes are assumed to be equipped with a single interface. Since WLAN mesh MPs are assumed to be static, node positions are fixed throughout the simulation. We do not consider the situation in which the topology changes might occur due to malfunction of MP, physically removed or any changes in the regulatory requirement. All links are bidirectional, reason being the uniform transmission range for MPs set to 250m. The neighbor discovery is performed through the exchange of beacon messages. When each MP is powered on, one channel is randomly assigned among three available orthogonal channels (namely, 1, 2 and 3). Similarly the CPI for each MP is computed as a sum of random value and the time the node is instantiated. In both implementations (SCUP and the proposed scheme), the switch announcement timer is set to 2 seconds, by an MP before transmitting the switch announcement frames.

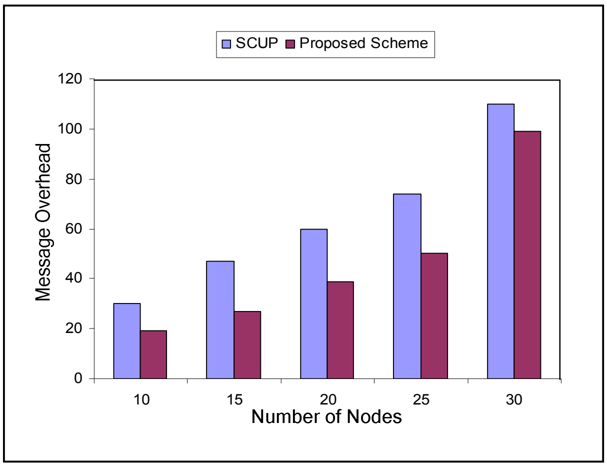

Figure 4. Message Overhead versus Number of Nodes.

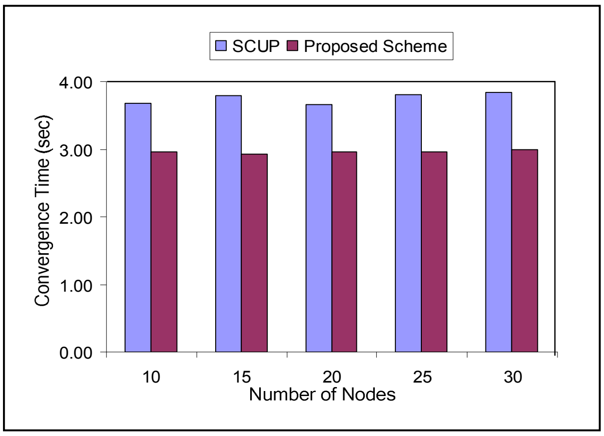

Figure 5. Convergence Time versus Number of Nodes.

Figure 4 shows the message overhead and Figure 5 shows the time overhead of our proposed scheme and the existing protocol SCUP. In Figure 4, we can see that the number of announcement frames increase as the number of nodes increase. In real situations, the booting time of MPs might be different due to which the channel convergence shall be more systematic and efficient. Nevertheless, our scheme performs better because the CPI depends entirely upon the random value in case of the SCUP. Any node can have better CPI value that might force the bigger sized UCGs to switch the channel. Therefore, it requires more number of switch announcement frames to converge. In our scheme, clusters of UCGs are formed started by the nodes that have the highest number of neighbors. Switch announcement frames are transmitted to smaller sized UCG reducing the amount required for convergence.

Figure 5 shows that our proposed scheme converges to a single UCG faster than the SCUP protocol for all topologies. Our protocol converges in an average of 3 seconds while the SCUP takes an average 4 seconds. Faster convergence implies faster topology generation in which normal operations of network such as data transmission can start earlier. In real scenarios, an MP might join very late in the WLAN mesh, or such MP joins the disjoint UCGs depending upon when it is enabled. In such cases the convergence time might take longer in SCUP and disturb the ongoing data communication. Since our scheme chooses smaller UCGs to be merged to the larger one, time required shall be even lesser in the real scenarios.

From the perspective of both time and message, we show that exploiting topology information is beneficial while forming the topology in the IEEE 802.11s WLAN mesh.

V. CONCLUSION

In this paper, we presented an enhancement on simple channel unification protocol and channel cluster switch protocol specified in the draft specification of the IEEE 802.11s. We argue that the topology formation process incurs high overhead and have longer convergence time if the protocols are unaware of the topological information. The enhancement can be made by including the size and identification of unified channel graphs. Our simulation results show that exploiting such information can improve the performance considerably, both in terms of time and message overhead.

In future, we will work towards constructing multiple UCGs in presence of MPs with one or more interfaces and multiple channels. We are also investigating on other research issues for channel selection and dynamic channel switching algorithms focusing on IEEE 802.11 based WLAN mesh networks.

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