An Intelligent Wireless Mesh Network Backbone

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ABSTRACT

In this paper, we report on a work-in-progress of an intelligent wireless mesh network backbone. We give a list of guidelines that should be considered for the design of such a network, and analyze them in the context of different application scenarios. We propose a backbone for these networks with the following characteristics: self-formation and maintenance, adaptability, and resiliency. A model for the backbone and a topology control scheme are proposed based on an analysis of the traffic flows generated by final users.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design – wireless communication, network topology.

General Terms

Performance, Design, Theory.

Keywords

Algorithms, Reliability, Theory.

1. INTRODUCTION

Wireless Mesh Networks (WMN) are a generalization of Wireless Ad-Hoc Networks that considers the use of heterogeneous nodes (e.g., clients and routers) and both wired and wireless connections to exchange data between these devices. The basic architecture of a WMN consists of a backbone of mesh routers (MR) and the clients that access communication services through the use of this backbone [1] (Figure 1). Therefore, this backbone serves as a last mile solution that is interconnected to provide direct communication between clients (i.e., without routing the inter-client traffic through any other intermediate network). This characteristic of a WMN enables it to function as an isolated autonomous network or as a last mile solution depending on the telecommunication facilities available at the place where the WMN is deployed. Some of the MRs possess different functionalities to provide communication services to the clients. For example, MRs with a gateway capability are able to connect the WMN to other networks such as the Internet.

To integrate the WMNs with real applications, the protocols, standards and algorithms used for the MRs should consider the current and widely deployed technologies (e.g., Ethernet, IEEE 802.11 and TCP/IP v4 and v6), and new emerging technologies (e.g., IEEE 802.16). Also, the theory, techniques, and algorithms already developed for the Wireless Mobile Ad-Hoc Networks (MANETs) should be considered.

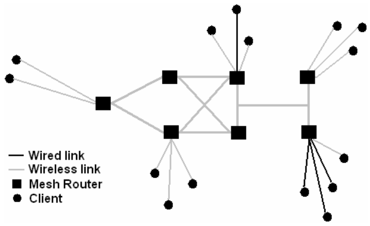

Figure 1. Wireless Mesh Network Architecture

Based on these observations, it is reasonable to think of a WMN that adapts its backbone according to its clients' needs and the telecommunication facilities available in the place where it is deployed. Therefore, this backbone should be an intelligent autonomous system capable of organizing, managing and healing itself. In this way, several application scenarios would be feasible for the WMN to provide telecommunication services such as wireless Internet access where current commercially available technologies do not do it in an efficient way or do not do it at all. Examples of these scenarios include low user density zones such as suburbs and rural areas, disaster recovery scenarios, campus, and enterprise buildings [1].

The first step to take for the deployment of the proposed intelligent WMN backbone is what we have defined as Wireless Mesh Network Formation (WMNF). It consists of first, making the backbone aware of the available telecommunication services; second, estimating the number of clients and formulating an appropriate client distribution; third, determining the topology of the network according to the clients' needs and available services; and fourth, maintaining and adjusting the topology according to changes in clients, services, and/or number and location of MRs.

In this paper, the WMNF problem is analyzed for a wireless Internet application scenario. Our approach aims to improve the throughput and delay in a WMN by controlling the link conflict graph (LCG) which is determined by the network topology. This control can be implemented based on transmission power control and/or antennas. Our approach is based on transmission power control; the antenna beam pattern is assumed to be given and

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fixed. The objective is to enable the WMN to adapt its topology according to the traffic patterns set by the applications running in the network (e.g., Internet access) and the available communication resources (e.g., gateways). Therefore, the WMN intelligently adapts its topology and LCG so that flows in the network can be established with lower levels of interference within and between them (i.e., intra-flow and inter-flow interference) through nodes that introduce less amount of delay in order to increase end-to-end throughput and decrease end-to-end delay.

In section 2, the related work is discussed. In section 3, the WMNF problem is characterized in more detail. In section 4, the proposed WMN system is presented, including the intelligent WMNF backbone model and the proposed approach for topology control. Section 5 concludes this paper.

2. RELATED WORK

The research literature in this area has focused on creating opportunities for higher throughput and optimal performance in terms of QoS and resource utilization. Thus, work has involved implementing an optimal scheduling scheme for the links established between the nodes, an optimal routing strategy, and an optimal congestion control technique. In [4], the authors propose a congestion control technique that reroutes flows that are competing for the same network resources so that other resources that have a low utilization are used more efficiently by the flows. In [10], a price-based approach for the optimal resource allocation is proposed. When too many flows compete for a limited resource, the price for utilizing this resource is increased and the flow sources decrease their rates in order to decrease the cost of utilizing this resource. In [6], a coordinate system based on the level of interference between nodes is proposed. Given low interference perceived by links in a path, the transmitting rates can be increased, which in turn increases the throughput.

Transmission power control for improving the network performance at different layers has been proposed based on optimization techniques [2]. However, the physical links between the nodes are considered given and fixed. Another power control technique for improving throughput and energy consumption is finding the minimum transmission power for each node such that the network remains connected [8]. In [5], the power control is done on a per-packet basis by transmitting each packet through the links that require the less amount of power, and in [7], the spatial reuse is increased by making each receiver advertise the amount of interference it can tolerate and allowing transmitters in its neighborhood transmit at power levels that do not cause the interference to increase above that level.

These solutions are only valid when the traffic in the network is heavy, so that the flows can be routed through links that cause low levels of interference to neighboring links. However, under different traffic characteristics, the increase in the number of hops and decrease in the network connectivity due to the transmission power reduction may negatively affect some network performance metrics such as end-to-end throughput and delay.

The techniques proposed above also assume a given and fixed network topology. Our approach aims to improve the network performance by adaptively controlling the network topology based on power control. Therefore, the nodes can be enabled to modify the LCG in order to manipulate the congestion patterns according to the traffic patterns determined by the applications running in the network. The LCG can be controlled by modifying the topology of the network, and this can be achieved by controlling the shape and the area covered (i.e., coverage) in the transmissions of each node. The coverage can be controlled by transmitting power control and antennas, and is affected by the obstacles encountered in the radio-channel.

3. WIRELESS MESH NETWORK FORMATION

3.1 The WMNF problem

The philosophy of the proposed intelligent WMN backbone is to provide an independent autonomous telecommunication infrastructure capable of organizing and maintaining itself, and adapting and integrating its topology with its environment by considering the clients' needs and capabilities and the available telecommunication services in the place where the backbone is deployed. In this way, the backbone would provide final users with an easy deployment of the network and less maintenance needs, and would also increase the number of scenarios where the backbone can be used. It should be noticed that the backbone could serve as a last mile solution or as an independent telecommunication infrastructure for building a network. The functionalities included in the MRs would determine the final capabilities of the intelligent WMN backbone.

In the WMNF problem, the objective is to find the optimum topology of the WMN in terms of throughput and delay according to the traffic patterns established between the user's applications (e.g., Internet access) and the network's services (e.g., gateways). The calculation of this topology considers multi-channel, multi-rate, and transmission power control capabilities of the nodes. In this problem, the location and number of MRs and clients are given. The solution is the set of links that efficiently (i.e., high throughput and low delay) allows communication from all the devices in the WMN (i.e., MRs and clients).

3.2 WMNF guidelines

We propose the following guidelines for finding the solution of the WMNF problem.

Autonomous formation and maintenance: It should be possible for final users with very basic knowledge about telecommunication systems to seamlessly deploy a WMN, and for experienced engineers to achieve a good performance if the network is more carefully designed.

Backbone centered: The MRs should be designed such that most of the burden for building and maintaining the WMN backbone is carried by them. In this way, the WMN dependence on its clients' capabilities and available telecommunication services is minimized.

Adaptability: Negative changes in the environment should have the less possible effect on the network performance. Positive changes should be utilized for improving the performance. Therefore, the network should adapt itself to these changes.

Resilience: The dependence on any centralized controller should be avoided for the solution to be resilient. The WMN backbone should not depend on a specific entity for its correct operation. It should rely on the capabilities enabled in different routers in a distributed way.

3.3 Cluster-based approach

We plan to follow a cluster-based approach which considers the following aspects. The MRs should be able to coordinate coverage of the area so that the interference caused between them is minimized (i.e., spatial reuse) by means of transmission power control. Given that the level of this interference will affect the transmission rate (i.e., multi-rate capability) of the nodes, the power control should establish power levels that allow the nodes to transmit at the necessary rates in order to provide the required end-to-end throughput. The transmission power control mechanism should also modify the topology of the network by creating and eliminating physical links between the nodes. In this way, links that are not efficiently used or not used at all can be eliminated so that communication resources are made available to improve the performance of other links and/or to create new links with better performance. The MRs should also coordinate the creation and elimination of physical links in different channels (i.e., multi-channel capability). For example, links that are spatially close to each other should be established in different channels in order to reduce the interference and improve the frequency reuse. Finally, any topology control technique for the WMNF should consider the trade-off between assigning communication resources for the relay of information within the backbone and assignment of resources for the access of clients to the network. The wireless transmissions for carrying these two types of traffic have to be done using the same channel(s) and space; therefore, the cluster formation procedures should consider the relaying traffic that passes through the clusters as well as the traffic coming from and going to final users.

4. PROPOSED WMN SYSTEM

Based on the WMNF guidelines, we propose the following system components for doing the WMNF: Access Station (AS), Subscriber Station (SS), and Base Station (BS). The AS is the system component used for giving the final user access to the WMN. An AS has low maximum transmitting power; it does not necessarily relay other users' traffic; it can switch channels, but only one channel can be used at a time, and it can adapt the transmitting rate according to the channel conditions (i.e., multi-rate). The SSs are the system components used for relaying traffic in the WMN. Therefore, SSs carry all the users' traffic and connect the ASs to the network. Also, SSs can transmit in different channels simultaneously at higher transmitting powers. They can transmit on a multi-rate basis too. The BSs connect the WMN to other external networks such as Internet and have the same capabilities of the SSs.

An example scenario is given in Figure 2. In this scenario, one BS provides wireless Internet access to the ASs through the SSs. Given that the ASs do not relay traffic, they form clusters around the SSs for accessing Internet.

The proposed WMN system follows two of the WMNF guidelines. The system is backbone centered because the ASs are not required to relay external traffic nor to transmit at high powers. The SSs and BSs form the intelligent WMN backbone that carries the network traffic and gives access to the ASs. The system can support distributed procedures that make it resilient to failures; for example, if the BS fails, the network could still operate autonomously and without access to any other external networks; if an SS fails, other SSs could still give access to the affected ASs provided that these are within their coverage area.

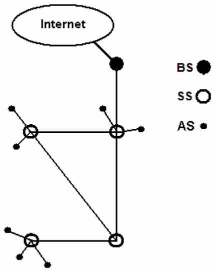


Figure 2. WMN example scenario

4.1 Intelligent WMN backbone model

The intelligent WMN backbone (see Figure 3) is modeled as a 3D graph whose nodes are the SSs and BSs, and whose edges are the bidirectional links between these devices.

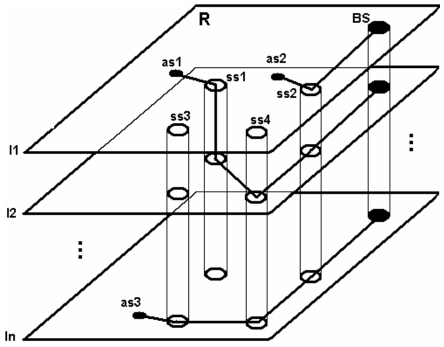


Figure 3. WMN system model

Let's suppose that a region R is to be covered with a WMN. (The region presented in Figure 3 is square, but it could take any other 2D shape.) There are n channels, represented by the n layers in Figure 3. Layer l1 is assigned to channel 1, layer l2 is assigned to channel 2, etc. The nodes are arbitrarily located in the region and are able to transmit at any of the channels, as illustrated by the vertical cylinders in Figure 3. It is assumed that the max power graph of the network is cross-layer connected. We say that a graph is cross-layer connected when there is at least one cross-layer path (i.e., a path that may traverse one or more layers) between any two nodes. Therefore, the 2D max power graph at each layer does not necessarily have to be connected. Within a layer, a path can take any direction. Between layers, a path can only take one straight vertical direction (i.e., it must begin and end in the same node).

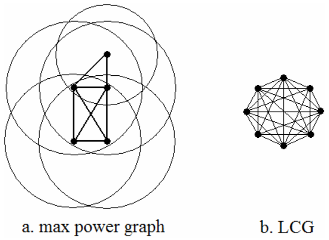
The interference model at each layer is the protocol model specified in [3]. The transmitting ranges of the nodes in the WMN system model do not necessarily have to be equal. Therefore, the coverage of the nodes may be different from each other. A link between two nodes is established if and only if the two nodes are within each other's coverage area (i.e., the links are bidirectional). The co-channel interference is zero, so there is no interference between layers.

The nodes are fixed in terms of mobility, but they may spontaneously appear and disappear. An AS must be in only one layer at a specific time, while an SS and a BS can be present in one or more than one layers at the same time.

4.2 Proposed topology control mechanism

Our topology control mechanism is based on the max power graph [9] of the WMN, including the set of all its subgraphs, and the LCGs of each of these graphs. The max power graph includes all the physical links that can be established in the network. The power assignment (PA) is the set of transmission power assigned to the nodes. Therefore, the network topology induced by any PA is always a subgraph of the max power graph. The LCG of each topology includes all the conflicts between links due to interferences between them [11]. In the LCG, each node represents one of the links between the nodes of the WMN, and each link represents a conflict (i.e., interference) between two links of the WMN. In order to successfully transmit a packet between two nodes of the WMN, none of the neighboring links that conflict with the intended path link can be active, i.e., in the LCG, none of the neighbors of the node that represents the link between the two nodes of the WMN can be active.

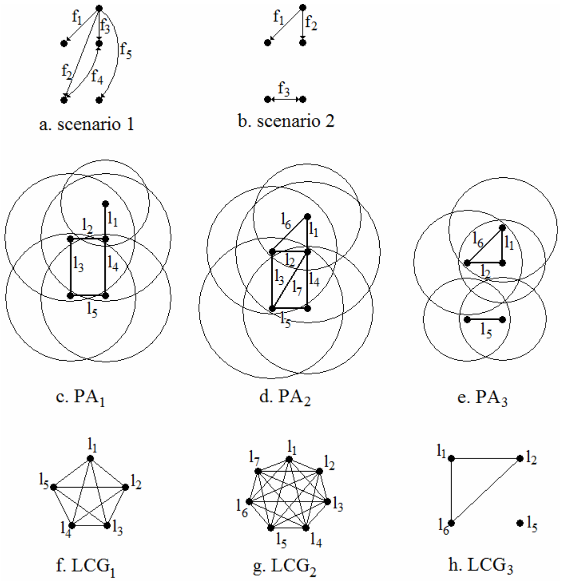
We assume that the max power graph of the WMN shown in Figure 2 is the same at each layer and is given by the graph that is in Figure 4a. Its LCG is shown in Figure 4b.


a. max power graph

b. LCG

Figure 4. Max power graph

In Figure 5, we give two examples of our topology control mechanism for increasing throughput and decreasing delay. Let's assume two different scenarios for the WMN proposed in Figure 2. These scenarios are characterized by the flows established between the nodes. In scenario 1, there are five flows (f_1-f_5) as shown in Figure 5a. In scenario 2, there are three flows (f_1-f_3) as shown in Figure 5b. The objective is to find a PA that maximizes the end-to-end throughput and minimizes the end-to-end delay of all the flows. Omnidirectional antenna beam patterns are assumed as well as equal transmission and interference ranges in this example. Each PA induces a set of physical links between the nodes. A link is established between a pair of nodes if and only if the nodes are within the coverage area of each other (i.e., the links are bidirectional). Two PAs are evaluated for each scenario, and for the purposes of this example, two PAs are considered equal if they induce the same set of physical links. The first PA (PA_1) for both scenarios is the set of minimum transmission powers such that the network is connected. PA_1 is shown in Figure 5c along with its induced physical links (l_1-l_5). The second PA for scenarios 1 and 2 (PA_2 and PA_3 respectively) are the PAs calculated based on our topology control approach for each of these scenarios. PA_2 and PA_3 are shown in Figures 5d and 5e along with their induced physical links. PA_2 induces links l_1, l_2, …, l_7, and PA_3 induces l_1, l_2, l_5, l_6.



a. scenario 1

b. scenario 2

c. PA_1

d. PA_2

e. PA_3

f. LCG_1

g. LCG_2

h. LCG_3

Figure 5. Topology control examples

The PAs of scenarios 1 and 2 are compared in Tables 1 and 2 respectively. In this comparison, it is assumed that the MAC layer follows a TDMA scheme, the data link transmissions are acknowledged (e.g., 802.16 mesh mode), all the packets have the same length, and that each node transmits no more than one packet per slot at a determined transmission rate common to all nodes. The comparison is based on the number of slots required to transmit one packet through each of the flows (i.e., one packet from the source of each flow to its destination); therefore, it is assumed that all the flows experience the same throughput. The number of slots is calculated based on the LCG induced by each PA. The LCGs of PA1, PA2, and PA3 are shown in Figures 5f, 5g, and 5h respectively where the i-th link is represented by node l_i. These are called LCG_1, LCG_2, and LCG_3. In each LCG, only one of the links that belong to one same clique can be active during one time slot otherwise collisions occur. Therefore, the maximum number of links that can be scheduled to be activated simultaneously for packet transmissions without collisions during one time slot is equal to the number of cliques in the link conflict graph. In LCG_1 and LCG_2, there is only one clique and all the nodes belong to it. Therefore, only one link can be active at a time in the network topologies induced by PA_1 and PA_2. In LCG_3, link l_5 and only one of the other links (i.e., l_1, l_2, and l_3) can be active simultaneously. The number of slots *ns* is determined based on the LCGs, and this number will determine the end-to-end throughput *x* and the maximum end-to-end delay d_{max} experienced by one of the flows according to (1) and (2):

$$x = \frac{c}{ns} \tag{1}$$

$$d_{\max} = ns \cdot T \tag{2}$$

where *c* is the link capacity, which is assumed to be the same for all the links, and T is the slot time length. From (1) and (2), it is concluded that the best performance is achieved when the number of slots is minimized.

Table 1. Comparison of PA1 and PA2 for scenario 1

		f_1	**f_2**	**f_3**	**f_4**	**f_5**	**ns**
Scenario 1	**PA$_1$**	l_1, l_2	l_1, l_2, l_3	l_1	l_2, l_3, l_3, l_2	l_1, l_4	12
	PA$_2$	l_6	l_1, l_7	l_1	l_7, l_7	l_1, l_4	8

Table 2. Comparison of PA1 and PA3 for scenario 2

		f_1	**f_2**	**f_3**	**ns**
Scenario 2	**PA$_1$**	l_1, l_2	l_1	l_5, l_5	5
	PA$_3$	l_1	l_6	l_5, l_5	2

The links used for the paths established for each of the flows are specified in Tables 1 and 2. These links were chosen based on a minimum number of hops metric (i.e., each packet is transmitted from the source of the flow to its destination through the path with the minimum number of hops). In scenario 1 under PA$_1$, there are a total of 12 link activations (i.e., 12 hops) for carrying one packet from each of the flows' sources to their destinations. Given that in LCG$_1$, all the links belong to the same clique, only one link activation is possible during a time slot. Therefore, 12 slots are required in this case. In scenario 1 under PA$_2$, there is a total of 8 link activations, and 8 slots are required because of the same reason (i.e., all the links belong to the same clique in LCG$_2$). In scenario 2 under PA$_1$, there is a total of 5 link activations, and 5 slots are required. In scenario 2, under PA$_3$, there is a total of 4 link activations, and only 2 slots are required because link l_5 does not belong to the clique that the other links l_1, l_2, and l_6 belong to (i.e., l_5 can be active with l_1, l_2, or l_6 simultaneously). These results show that PA$_2$ and PA$_3$, which are based on our topology control mechanism, outperform PA$_1$ in both scenarios because a less number of slots are required.

The previous two examples also show that the LCGs of each of the topologies induced by PAs will determine the necessary number of slots ns for each PA. Based on this observation, we propose the following problem to be solved by our topology control mechanism in order to minimize *ns*: Find the PA from the set of all possible PAs that has the minimum number of activated links that belong to one same clique of its LCG and that has the maximum number of activated links that belong to different clicks of its LCG such that these links belong to the paths used by the flows and calculated on a minimum number of hops basis.

5. FUTURE WORK

Based on the proposed analytical model for the intelligent WMN backbone, we plan to develop algorithms for the autonomous network formation and maintenance, adaptability, and resiliency of the backbone based on topology control mechanisms such that the end-to-end throughput and delay are maximized and minimized respectively. Also, wired links between the nodes will be included in the model in order to integrate the WMN backbone with already deployed infrastructure such us Ethernet. For evaluating the algorithms and the impact of topology control on routing algorithms, a simulation model will be developed. The integration of our topology control mechanism with 802.11 and 802.16 mesh mode is planned to be considered.

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