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# DESIGN ISSUES IN INFRASTRUCTURE WI-FI MESH NETWORKS

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**Abstract:** Infrastructure Wi-Fi mesh networks are foreseen to be a major technology in future wireless systems. A major characteristic of this type of networks is that it provides a wireless backbone, that is, the wireless access points in the backbone communicate with each other. Wireless backbone provides many benefits which include low infrastructure wiring cost, high capacity and coverage, and better system scalability. With these benefits, infrastructure Wi-Fi mesh networks can be used in many environments such as public hot zones and urban area. However, designing this type of networks requires the considerations of many issues. In this paper, we study these issues in details and give insights into the future research direction of the wireless system development.

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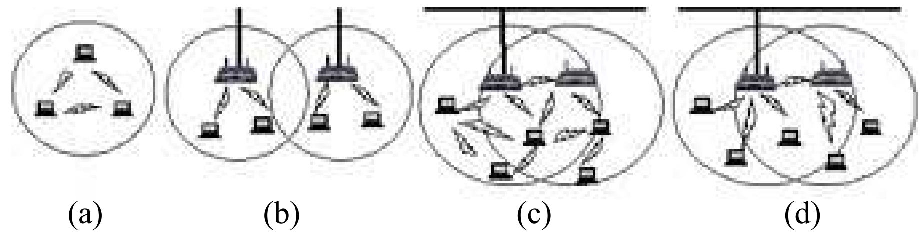


Figure 1: The system architectures of: a) IEEE 802.11 ad-hoc network, b) IEEE 802.11 infrastructure network, c) wireless mesh networks and d) Infrastructure Wi-Fi mesh networks

## 1. Introduction

Wireless communication systems have evolved rapidly in recent years. Among them, wireless LAN is one of the successful and widely used systems. Most current wireless LANs are based on the IEEE 802.11 standard which defines two wireless LAN configurations: ad-hoc mode and infrastructure mode. A wireless LAN operating in ad-hoc mode, as shown in Figure 1(a), is a local peer-to-peer network in which the mobile clients directly communicate with the nearby clients, without the need of central coordination. This mode is usually used among the trusted clients under co-operative environments, such as conference meeting and home networking.

The wireless LAN configuring in infrastructure mode is a two-level hierarchical system in which wireless clients communicate with other clients through access points (APs) (see Figure 1(b)). All frames sent from a client must go through its associated AP, which in turn forwards the frames to the destination. An AP is usually connected to a wired network via wired lines, acting as a bridge between the wired and wireless networks.

Wireless mesh networks (WMNs), as shown in Figure 1(c), are a new type of wireless LAN which inter-connects all APs and mobile clients wirelessly. WMNs combine the architectures of both infrastructure and ad-hoc modes of IEEE 802.11 wireless LANs, consisting of mesh APs and mesh clients. The mesh APs in a WMN connect together via wireless links to form a wireless backbone. On the other hand, the mesh clients form a peer-to-peer network and access the backbone via the mesh APs. To facilitate communications over the WMNs, multi-hopping transmissions through mesh APs and clients are required. In the other words, the traffic may have to go through a number of clients and APs before reaching the destinations. This requires the clients to perform additional operations such as routing and self-configuration. However, the WMNs are not suitable for the large open areas because their mesh clients are assumed to be applicable in the private environments.

Infrastructure Wi-Fi mesh networks are another new type of wireless networks as shown in Figure 1(d). Unlike WMNs, these networks use mesh APs but not mesh clients. This makes implementation realistic in large public areas. On the other hand, the wireless backbone in infrastructure Wi-Fi mesh networks eliminate the costs of installing wired backbone network and also flexibly increase network capacity and coverage. Furthermore, since infrastructure Wi-Fi mesh networks are based on the standardized IEEE 802.11 technology, the network compatibility can be enhanced. This advantage enables viable integration of infrastructure Wi-Fi mesh networks with other communication systems. With these features, infrastructure Wi-Fi mesh networks are foreseen to be one of the next widespread broadband access technologies (see [2], [3], and [6]).

There is a number of existing infrastructure Wi-Fi mesh networks. For example, tropos networks implements the networks, and calls it MetroMesh, in the cities of United States [8], [9], and [10]. Nortel networks also announces general availability of its infrastructure Wi-Fi mesh networks solution [11]. Their goals are to design networks which go beyond the traditional Wi-Fi hot spots, so that the wireless coverage can be increased to cover a larger geographic area. Recently, Wi-Mesh alliance [12], formed by Nortel Networks and the industry leaders, developed and submitted a standard proposal of infrastructure Wi-Fi mesh networks to the IEEE 802.11 task group S. As can be seen, the development of infrastructure Wi-Fi mesh networks is highly concerned. However, developing an efficient and reliable infrastructure Wi-Fi mesh networks involves many design issues in different areas. Some have been solved but most of them have not been well formulated. Therefore, in this paper, we study the design challenges and possible solutions so as to give insights into the development of infrastructure Wi-Fi mesh networks.

## 2. Design Issues

The design issues in infrastructure Wi-Fi mesh networks can be divided into two groups. The first group concerns the issues related to physical layer, whereas the second concerns the issues related to MAC layer. The issues are summarized

| Layer | Design Issues | |
|---|---|---|
| PHY | System Architecture | Topology and Layout |
| | | Hardware Design |
| | Capacity and Coverage | Traffic Engineering |
| | | Bandwidth Fairness |
| | | Coverage Planning |
| MAC | Layer 2 Routing | Static Routing |
| | | Dynamic Routing |
| | Frame Forwarding Protocols | Frame Duplication in Broadcast and Multicast |
| | Security | Security Threat |
| | | Security Defence |
| | QoS | Types of Service |

Table 1:

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### 2.1. Physical Layer

1) System Architecture

*i) Topology and Layout.* Although infrastructure Wi-Fi mesh networks are based on IEEE 802.11 networks, their network topologies are different. As shown in Figure 2, some APs could connect to the wired network using wired lines and simultaneously connect to other APs wirelessly, we call them edge APs, whereas some only connect to other APs wirelessly, we call them relay APs. The relay AP relays the clients traffic to nearby relay AP which in turn relays to the traffic to another relay AP until an edge AP is found. It can be seen that the load of an edge AP is sensitive to the number of relay AP connecting to it. Therefore, a detailed planning in the layout and density of the APs is required to avoid network congestion and minimize system cost.

*ii) Hardware Design.* Additional operations are performed in the APs of infrastructure Wi-Fi mesh networks; this increases the complexity in the hardware design. For example, in capable of relaying traffic to other nodes, the APs are required to perform layer 2 routing. Although routing algorithms can be implemented in software, the APs are expected to have enough processing power. Also, the memory requirement in keeping the routing information in the APs is increased.

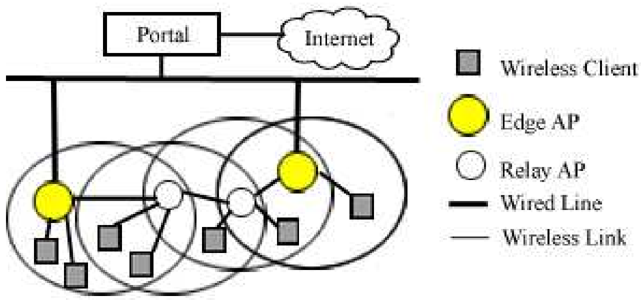


Figure 2: The topology of infrastructure Wi-Fi mesh networks

On the other hand, to use as effective backbone, multiple antennas using multiple radio frequencies are usually applied in infrastructure Wi-Fi mesh networks. Multiple-in-multiple-out (MIMO) antenna uses this technology to increases the aggregate capacity of the mesh networks. *Hyacinth* is a multi-channel wireless mesh network architecture which supports distributed channel assignment to increase the overall network throughput [2]. It is shown that by equipping each node with three network interface cards can increase the network bandwidth by a factor of six to seven as compared with single-channel mesh network architecture. Although MIMO is being used in some of today's Wi-Fi networks, applying MIMO in the mesh networks adds difficulty in channel assignment planning which tries to reduce interference and increase the system bandwidth.

Power consumption is the next hardware design issue of the wireless APs. Since infrastructure Wi-Fi mesh networks are designed for the deployment in urban areas where may not have adequate support of power lines, researchers should not only focus on reducing the power consumption of the devices, but also they should try to seek new electricity sources. Electricity over the air, solar energy, dry batteries or wind energy can ease the power demand of the networks. However, less discussion is reported in this area in the literature.

2) Capacity and Coverage

*i) Traffic Engineering.* Traffic engineering uses statistical techniques such as queuing theory to predict and engineer the behaviours of communication networks. Efficient traffic engineering helps increasing system throughput as well as reducing congestion in the networks. In order to predict the system traffic and build the system model precisely, some basic parameters such as

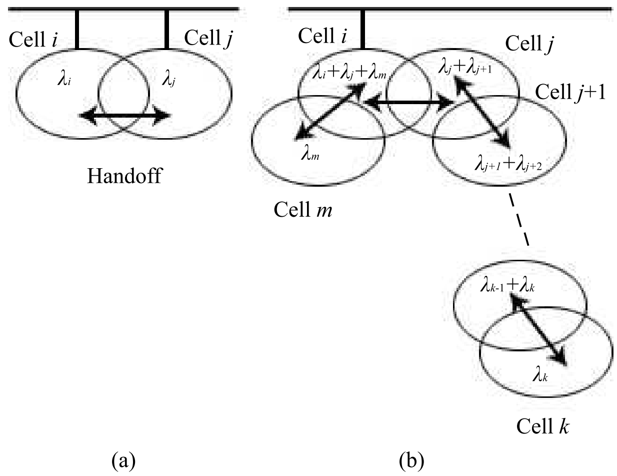


Figure 3: The arrival rates of the cells in: a) today's Wi-Fi network and b) infrastructure Wi-Fi mesh networks.

arrival rate are necessary. In today's Wi-Fi networks, APs are connected to the wired network; data originated by the mobile clients will be forwarded to the wired network via their associated APs. In the other words, APs serve the mobile clients in their cell in which the traffic can be straightforwardly monitored and modeled.

However, monitoring and modeling infrastructure Wi-Fi mesh networks is not an easy task. Let $\mathrm{AP}_i$, $\lambda_i$ denote the AP and independent arrival rate of cell $i$ respectively. As shown in Figure 3, $\mathrm{AP}_i$ is connected to the wired network but $\mathrm{AP}_j$ is not; the uplink traffic from cell $j$ will be routed to cell $i$ so as to reach the wired network. When the traffic of cell $j$ is routed to cell $i$, the actual arrival rate of cell $i$ is $\lambda_i$ plus $\lambda_j$. However, at the same time, cell $j$ aggregates the traffic from cell $j+1$. Therefore, in general, the actual arrival rate of cell $i$ becomes $\sum \lambda_k$ where the traffic in cell $k$ is eventually supported by cell $i$. As the dynamic routing protocol used among the APs forms dynamic routes in the networks, it increases complexity in estimating the system traffic and building a precise system model of infrastructure Wi-Fi mesh network.

To simplify the work, researchers can make some assumptions in studying traffic engineering such as defining the average number of extended cells that can be served per cell, fixing the number of APs connecting to the wired network, defining the handoff rate, modeling different types of mobile users, and classifying types of application. Nonetheless, it is still challenging to realize efficient and promising traffic engineering.

*ii) Bandwidth Fairness.* In addition to traffic engineering, allocation of system resources in a fair and efficient way is particularly essential to maintain stable performance in infrastructure Wi-Fi mesh networks since they are expected to support high speed and time-sensitive data transmission in the backbone networks. Various scheduling mechanisms in dividing the limited bandwidth among the clients such as TDMA and FDMA have been widely used in the literature. However, it is harder to enforce fairness in infrastructure Wi-Fi mesh networks due to their dynamic traffic patterns and topologies. Besides developing an accurate system model to assist in allocating resources, the real time network status as an indicator can reflect the resource distribution effectiveness. On the other hand, a portion of bandwidth available in a cell can be reserved for its extended wireless cells and unexpected traffic. Bandwidth fairness is an advanced topic in realizing stable infrastructure Wi-Fi mesh networks; however, more comprehensive studies in co-operations among other mechanisms such as routing protocol and quality of service are definitely required.

*iii) Coverage Planning and Interference.* As mentioned in the topology and layout section, the network extends its coverage by proper locating and inter-connecting the wireless APs. However, interference which temporarily or permanently affects the quality of the transmission links may occur. Yet, the consequence of out-of-coverage in infrastructure Wi-Fi mesh networks is more serious than that in Wi-Fi networks. In [1], F. Tasaka et al quantify the degree of co-channel interference by the carrier to interference index (CIR) based on the distance between the terminal with a same channel. In order to keep CIR above a specific threshold to maintain the quality of communication, the authors design a new channel assignment algorithm. However, interference can be affected by many factors such as obstacles, multipath effect and transmission power of the terminal; more comprehensive studies simulating various environments and evaluating the system coverage are desired. Nortel networks designs a planning tool called mesh planner for simulating the deployment of the mesh networks. This indicates it is valuable to implement and setup infrastructure Wi-Fi mesh networks in coming future.

## 2.2. MAC Layer

1) MAC Routing MAC routing is one of the main challenges in implementing infrastructure Wi-Fi mesh networks. In current single-hop Wi-Fi networks, all access points connect to the wired network directly. They are simply responsible

to forward the uplink data to the static wired link and broadcast the downlink frame to its clients. However, some of the access points in infrastructure Wi-Fi mesh networks do not connect to the wired network directly; instead, they inter-connect with each other wirelessly. As a consequence, the mobile clients are usually multiple hops away from the wired network; and hence, routing protocol is required for a source to find a route to the destination. In the next two subsections, we discuss the design issues of the static routing and dynamic routing respectively.

*i) Static Routing Protocol.* Static routing protocol is usually used in a small scale network in which no dynamic topology change and traffic burst are expected. Before building static routes, the network administrator should have a clear understanding on the network topology, user behaviour, traffic statistic and available system resources. However, it is difficult to gather this information in infrastructure Wi-Fi mesh networks if they are designed for public access.

On the other hand, when the mesh networks are used as backbone networks in which the locations of the APs do not usually changed dynamically, the static route assignment is a key task in resource fairness. Nevertheless, we suggest that static routing is suitable for infrastructure Wi-Fi mesh networks in a secure private area such as a corporation. This is because simple routing protocol can reduce system overhead and complexity of the software and hardware designs. We also suggest that alarm mechanisms and backup protocols are needed to reduce the influence in routing failure. However, this area still requires more comprehensive and total-solution studies.

*ii) Dynamic Routing Protocol.* In view of the fact that wireless networks are unstable and bandwidth limited, the conventional dynamic routing protocol used in wired networks such as link state routing protocol is not suitable for the wireless mesh networks. This type of routing protocol requires each router to maintain at least a partial map of the network. Whenever there is a network link state change, a notification is flooded throughout the network. All the routers eventually note the change and recompute their routing information accordingly. This method is automatic and reliable; however, it may induce high overhead as the link state may vary frequently in wireless networks. On the same hand, there are many studies in routing protocols in ad-hoc networks. But, due to ad-hoc networks is a flat architecture, their routing protocols do not perform well in infrastructure Wi-Fi mesh networks. Nevertheless, the studies in ad-hoc networks can probably give some directions in designing routing protocols for the mesh networks.

Different network environments require different routing metrics to improve the network performance. In [4] and [5], the authors compare four routing metrics including Expected Transmission Count (ETX), Per-hop Round Trip Time (RTT), Per-hop Packet Pair Delay (PktPair) and Hop Count (HOP) by simulating a DSR-based routing protocol in a wireless testbed. It is shown that using the ETX metric outperforms when all mobile nodes are stationary but RTT and PktPair metrics perform poorly due to self-interference. Interestingly, the simple metric HOP outperforms all of the other three metrics if the sender is a mobile device because the first three metrics do not react sufficiently quickly to the network changes. Nevertheless, we believe that metrics which can reflect the system conditions have superiority over HOP metric since a long radio link with high loss rate may be picked under the hop count routing protocol. However, the key design issue is how these metrics react in order to update the APs with minimal latency. Also, automatic recovery mechanism is needed to for any system failure. This is especially important to infrastructure Wi-Fi mesh networks since the backbone APs handle a bundle of traffic from various sources that single failure may ruin the whole networks.

2) Frame Forwarding Protocols. *i) Frame Duplication in Broadcast transmissions.* In current Wi-Fi networks, a mobile client will discard any duplicated frame from its associated AP by checking a flag in a frame. However, in infrastructure Wi-Fi mesh networks, frame duplication can be occurred during broadcast and multicast transmissions. Figure 4 shows that AP A, B and C are closed together and able to communicate with each other. When the server broadcasts a frame, AP A and B which are connected to the server receive the frame. When AP A broadcasts the frame, both AP B and C receive it. At the same time, AP B broadcasts the frames received from the server and AP C gets it while AP C broadcasts the frame received from AP A to its client and so on. Finally, AP C receives three copies of the frame and broadcast all of them to its client. One of the solutions for this problem is using spanning tree protocol to limit the path of the broadcast frame. However, detailed study is required in this aspect.

3) Security. *i) Security Threats.* It is more difficult but important to secure the wireless mesh networks since security threats appear more often in the large scale wireless networks. In addition, security attacks in infrastructure Wi-Fi mesh networks not only able to harm a part of the network but also ruin whole mesh system as its cells are dependent on and communicate with each other. However, there is less studies in preventing security threats such as infrastructure exposure, routing attack, interference attack, denial of service and open data in frame body.

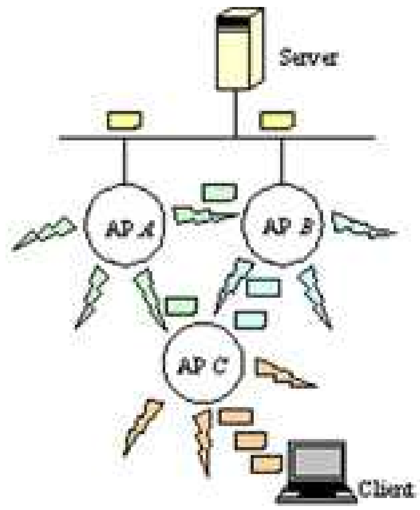


Figure 4: Frame duplicated during broadcast transmission in infrastructure Wi-Fi mesh networks

*ii) Security Defenses.* There are numbers of security mechanisms in wireless LAN such as WEP, WPA and IEEE 802.11i. However, they focus on securing the association between the mobile client and the AP only. Infrastructure security is required in protecting the mesh network to avoid the security threats mentioned in the last section. As discussed in [7], some security schemes proposed for ad-hoc networks but they are not applicable to infrastructure Wi-Fi mesh networks due to differences in system architecture. As a consequence, new security protection and monitoring schemes need to be developed.

4) Quality of Service. *i) Type of Service.* Data traversed in multi-hop wireless mesh networks decreases the end-to-end transmission reliability since collision or loss in packet transmission will occur more frequently. This can seriously degrade the overall system performance. IEEE 802.11e can provide QoS support for the wireless LAN applications, especially for the time-sensitive applications such as voice over wireless IP. However, being a part of backbone or wide area access network, infrastructure Wi-Fi mesh networks support more various applications with different QoS requirements. More performance metrics such as aggregate throughput, per-node throughput and package loss rate should be considered by the communication protocol.

## 3. Conclusion

This paper discusses the design issues in infrastructure Wi-Fi mesh networks. Some issues such as system architecture, capacity and coverage, and layer 2 routing have been well studied. However, the solutions regarding frame forwarding protocol and security issues have not been well defined yet. On the other hand, in order to facilitate a stable, fast and diverse system, more effort should be put in designing QoS mechanisms which have little concern currently.

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