Wireless Cooperative Mesh Network: A New Architecture for Network Convergence

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Abstract:
The convergence of heterogeneous wireless networks is a trend in the evolution of wireless networks. A new architecture for network convergence, named Wireless Cooperative Mesh Network, is proposed to solve such emerging problems in convergence as transmission mode selection, load balancing, routing and handover. The new architecture is based on the structure of Wireless Mesh Networks (WMNs), and cooperative communication is also employed to further optimize its structure and upgrade its performance. It can thus obtain advantages of both the Mesh technology (high spectrum efficiency and dynamic self-organization) and cooperative communication (high diversity gain and high energy efficiency). The new architecture serves as an efficient solution for wireless network convergence.

With the rapid development of wireless communications, many heterogeneous wireless networks are emerging to satisfy different application scenarios. These networks provide multiple choices for users in terms of bandwidth, coverage, Quality of Service (QoS) and accounting. The convergence of these heterogeneous networks is necessary to realize their interconnection[1]. Current researches on network convergence are focusing on the convergence of Ad hoc networks and cellular networks[2], exploiting the advantage of Mesh networks to overcome the coverage problem of point-to-multipoint communications.

Most of the current researches on network convergence are modifications and enhancements of existing networks. There is not yet a good scheme for network convergence. Therefore, much attention has been paid to the design of a new architecture for network convergence.

Wireless Mesh Network (WMN), which has the advantage of high spectrum efficiency, dynamic self-organization and low deployment cost, is considered to be a key technology for network convergence. As a complete network, WMN utilizes multi-hop relay to forward services between mobile terminals and fixed networks. WMN takes advantage of relay technology, which provides precondition for the implementation of cooperative communication. Cooperative communication can provide high diversity gain and high energy efficiency and is thus considered an important technology to enhance wireless communications. Based on WMN and cooperative communication, this paper proposes Wireless Cooperative Mesh Network, which is a new architecture for network convergence. This architecture is based on the Mesh structure, and cooperative communication is employed to further optimize its structure and enhance its performance.

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1 The Fundamentals of WMN

WMN[3], which is based on the Ad hoc technology and partly follows Wireless Local Area Network (WLAN) technology, is a new wireless network, totally different from traditional wireless networks. It has such advantages as easy networking, convenience, and scalability. It can be thought as the wireless version and miniature version of the Internet in network topology. It can also be granted as the convergence of WLAN and Ad hoc networks, and it takes advantages of both networks. As a new architecture to solve the bottleneck of last-mile communications, WMN has been adopted in IEEE 802.11, IEEE 802.15, IEEE 802.16 and IEEE 802.20 standards[4].

WMN can solve the scalability and robustness problem of WLAN. It is a breakthrough of wireless technology and can find applications in many aspects[5-7]. Generally, WMN is composed of user nodes, wireless Mesh routers and gateways, which change according to different network configurations. Mesh nodes can be laptops, Personal Digital Assistants (PDAs), Wireless Fidelity (Wi-Fi) handsets, wireless sensors and more. Mesh Routers can be ordinary PCs as well as specific embedded systems.

In WMN, Mesh routers are interconnected to form the wireless backbone, which has low mobility. The wireless Mesh backbone provides the gateway and routing between WMN and other networks, such as the Internet, cellular networks, WLAN based on IEEE 802.11, Wireless Personal Area Networks (WPAN) based on IEEE 802.15, Wireless Metropolitan Area Networks (WMAN) based on IEEE 802.16 and Wireless Sensor Networks (WSN).

Compared with traditional wireless routers, wireless Mesh routers have additional routing functionality to support Mesh connection. They can obtain the same coverage with much lower transmit power through wireless multi-hop communications. Mesh routers usually have several wireless interfaces based on the same or different radio access technologies to further improve the scalability of Mesh networks.

Mesh user nodes can be classified into two types. The first type is the ordinary WLAN user node, which does not have the function of information forwarding in the typical sense of mobile Ad hoc networks, and only accesses the network as an ordinary terminal. The other type can not only access the network but also route and forward information, i.e., it has the function of wireless routers.

WMN can be classified into three types according to the network structure, i.e., backbone Mesh structure, user Mesh structure, and hybrid structure. WMN can also be classified into another three types according to the structure layers, i.e., multi-level structure, plane structure, and hybrid structure. The following part will concentrate on the backbone Mesh structure, which is a multi-level structure. The backbone Mesh structure is composed of self-configurable and self-healing links formed by Mesh Routers. It is connected to Internet through the gateway function of Mesh routers and provides access services to users. Under this network structure, ordinary users and existing wireless networks can access the WMN through the gateway or routing function of Mesh Routers. The backbone Mesh structure is shown in Figure 1. The dashed line and the real line in the figure stand for wireless links and fixed links respectively. The wireless links use multiple radio technologies including

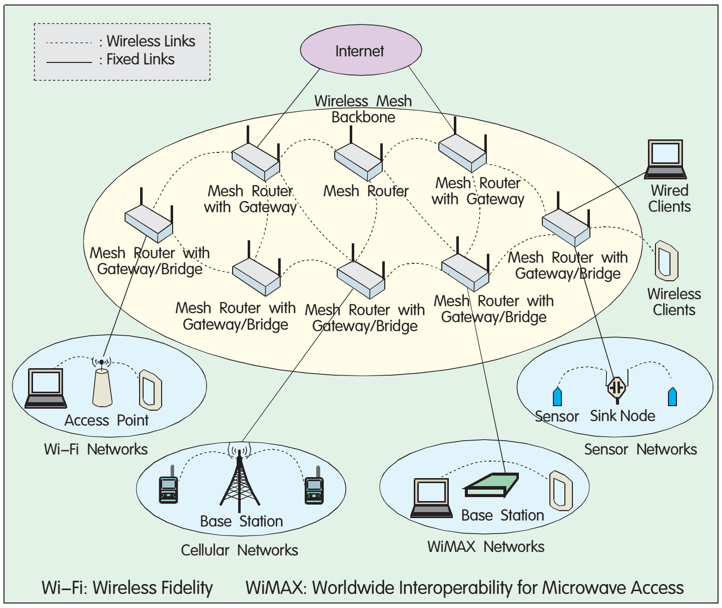


Figure 1. Backbone Mesh structure.

IEEE 802.11. Ordinary users with an Ethernet interface access the Mesh routers through Ethernet connection. If ordinary users use the same radio technology as the Mesh routers, direct connection can be set up. If different radio technologies are used, users have to access Base Stations (BSs) with an Ethernet interface before connecting to Mesh routers.

2 The Fundamentals of Cooperative Communications

Cooperative communications[8] is a new wireless technology which takes advantage of the broadcast nature of wireless communications, and obtains spatial diversity gain by relaying and forwarding signals and processing source signal and relay signal jointly on the receiver side. That is to say, cooperative communications is a communications scheme which is a parallel combination of direct communications and relay (multi-hop) communications. It is not a pure relay communications in the sight of signal processing. The Relays (Rs) in cooperative communications can be fixed relays or Mobile Stations (MSs) with the function of forwarding.

The basic mode of cooperative communications is shown in Figure 2(a). First, the source broadcasts information to the relay and the destination (e.g., BS). Second, the relay forwards the received signal to the destination (through Amplify and Forward, or Decode and Forward). Finally, the destination combines the two signals received in two time slots and detects the source information. Frequency Division Multiplexing (FDM) or Time Division Multiplexing (TDM) can be used to ensure the orthogonality between the source signal and the relay signal.

Figure 2(b) is the typical application form of cooperative communications, from which the following transmission modes can be derived.

(1) Cooperative Multiple Access

This mode supports uplink simultaneous access and can be further classified into two modes. In the first mode, extra relay nodes are employed to cooperate with all the source nodes. In the second mode, source nodes cooperate with each other, and there is no extra relay node.

(2) Cooperative Broadcast

This mode supports downlink unicast and broadcast.

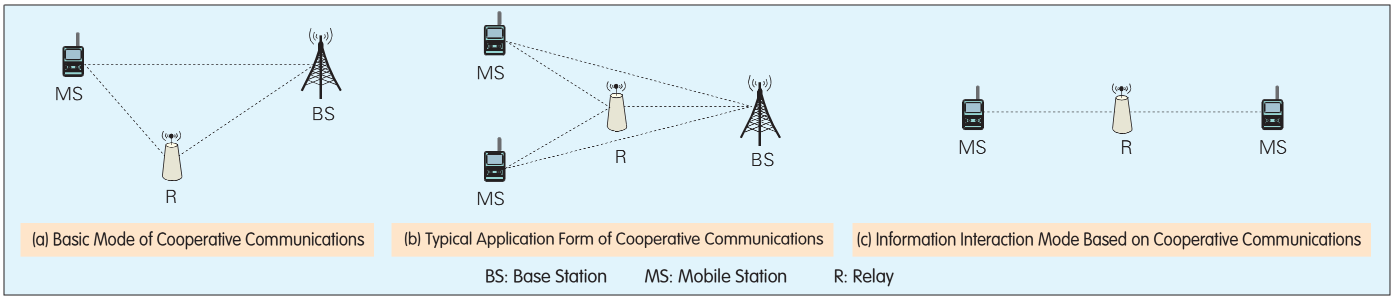
(3) Cooperative Reception

This mode fits point-to-point transmission. Taking wireless sensor networks for example, if the relay is very close to the destination (e.g., wireless Routers and more), cooperative reception can be utilized.

(4) Cooperative Transmission

This mode fits the scenario where the relay is close to the source.

Figure 2(c) is the information



▲Figure 2. Models of cooperative communications.

interaction mode based on cooperative communications, which fits peer-to-peer transmission.

In all the application models shown in Figure 2, the relay can be single or multiple, and parallel or serial. Research thus far has shown that cooperative communications perform much better than both single-hop and multi-hop communications.

3 Wireless Cooperative Mesh Network

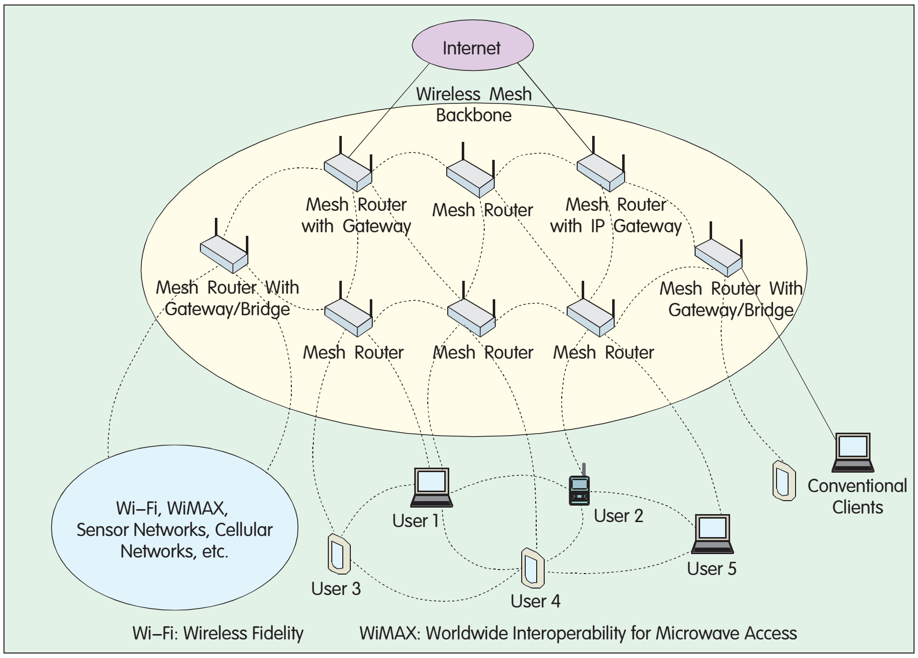
This paper proposes a new architecture for network convergence, named Wireless Cooperative Mesh Network, based on WMN and cooperative communications technology. The new architecture is based on the Mesh structure, and cooperative communications are employed to further optimize the structure and upgrade the performance of this architecture. The architecture is shown in Figure 3. First, the wireless Mesh backbone is formed by Mesh routers, and then the wireless Mesh user network is formed by users. Users have to access the wireless Mesh backbone to get service. Users close to the Mesh routers are connected directly to the wireless Mesh backbone, while those, which are far away from the Mesh routers, are connected to the wireless Mesh backbone through multi-hop. Besides, thanks to the introduction of cooperative communications, users can cooperate with each other to obtain higher performance. The operation mechanism of Wireless Cooperative Mesh Network will be discussed from the following four aspects.

3.1 Transmission Mode Selection

Multiple transmission modes are available in a convergent network, such as conventional cellular mode, Ad hoc mode, cooperative transmission mode, and more. Transmission mode selection is inevitable when more than one transmission mode can satisfy communications demand of users. Transmission mode selection includes two parts. The first is the transmission mode selection when communication is initiated, and the second is the transmission mode transition when communication is in progress. Different transmission modes will result in different transmission performance. Therefore, in order to obtain the optimal transmission performance, such factors as the utilization of network resources, load balancing, QoS and mobility have to be taken into account to select a transmission mode. Meanwhile, some metrics are supposed to be defined to measure a transmission mode selection mechanism, and an efficient optimization function has to be determined. When communications is initiated from a node, the node will independently select a path which bears the lightest load, or the BS will designate a path from the paths searched according to the network load and throughput.

3.2 Load Balancing

Load balancing is also a key problem in convergent networks. Researches have found that the amount of forwarding services a node bears is dependent on the location of the node and the node density around it. Nodes near the center of the network bear more forwarding services than those near the margin of the network. This will cause the nodes near the center of the network to drain their energy very fast and make the node



▲Figure 3. Wireless cooperative Mesh network.

density around the center lower, which will thus cause the load of other nodes in this region to become heavier and form a vicious circle. This kind of regional reduction of node density will not only result in the partition of the network, but also affect the services in progress and reduce the network throughput. Therefore, the problem of load balancing in convergent networks requires in-depth study. In the Wireless Cooperative Mesh Network proposed, a modification is made to the shortest-path criterion: multiple backup paths, instead of only one path, are searched.

3.3 Routing

The routing requirements of convergent networks are different from those of traditional cellular networks and Ad hoc networks. The multiplicity of transmission modes and the diversity of node types make the existing routing protocols of cellular networks and Ad hoc networks unsuitable for convergent networks. On the one hand, the multiplicity of transmission modes brings about new requirements for routing mechanism, and the transition between transmission modes has to be factored in the design of the routing mechanism of convergent networks. On the other hand, there are infrastructures laid beforehand, as well as some fixed relay nodes which are more capable in computing and storage. These relay nodes, which have full or partial functions of a BS, can obtain the location information of nodes and the topology information of the network within certain coverage region, and can thus assist the computing of routing and the selection of paths. Therefore, in the design of the routing mechanism of convergent networks, these nodes should be made full use of. In this way, the distributed routing is combined with the relay-assisted routing to enhance the network performance.

3.4 Handover

Handover is the most important supporting technology for mobile communications. There are two kinds of handover, i.e., horizontal handover and vertical handover. The former is the handover between different cells (sectors) within a network, while the latter is the handover between heterogeneous networks. The handover performance depends on cell frequency planning and capacity planning, which are closely related to the service model and service distribution. Proper capacity planning should aim at minimizing the handover block rate and at the same time maximizing the residual capacity. Current mobile services are both in burst and group. For instance, group handover requirements are produced when trains, buses or other vehicles are on the way. Although increasing residual capacity can solve the problem, this will cause a waste of network resources and increase the call blocking rate. Cooperative handover can be employed to solve the problem. The basic idea of cooperative handover is to balance the load through the utilization of cooperative communications. Traditional handover strategy is encountered with a dilemma to choose between received signal strength and cell blocking rate. In the Wireless Cooperative Mesh Network, the only criterion of handover is to access the adjacent cell which bears the lightest load, and cooperative multi-hop is employed to ensure the reliability of handover. Cooperative handover can be granted as a tradeoff of BS-controlled handover and mobile-controlled handover. The MS initiates the handover requirement, and then the cell, which bears the lightest load, computes the routing information and determines the path for the MS (i.e., designates relays to provide routing for the MS) according to the connection status of the network and at the meanwhile allocates corresponding bandwidth. Additionally, wireless routers can be fixed on vehicles to serve as the handover requirement agent for group services.

4 Conclusion

The convergence of heterogeneous wireless networks is a trend in the evolution of wireless networks. A new architecture for network convergence, named Wireless Cooperative Mesh Network, is proposed in this paper. With advantages of both Mesh technology (high spectrum efficiency and dynamic self-organization) and cooperative communications (high diversity gain and high energy efficiency), the new architecture serves as an efficient solution for wireless network convergence.

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