Mesh Networks: The Next Generation of Wireless Communications

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Conceived by the U.S. Military, mobile ad hoc networks, commonly known as mesh networks, provide end-to-end Internet Protocol (IP) communications for broadband voice, data, and video service combined with integrated geographical location logic designed to function in a mobile wireless environment. Unlike 802.11 wireless local area networks (WLANs) and point-to-multipoint digital cellular networks, mesh networks accommodate a more dynamic operational environment where their radio frequency (RF)-independent, self-forming, and self-healing properties meld the best of both worlds between WLAN and cellular systems. This paper examines the concept of mesh networks with a look at recent commercial and military development of what some consider a disruptive, next-generation wireless communications technology.

1. Introduction

Loosely speaking, mesh networks form a wireless Internet where any number of host computing nodes can route data point-to-point in an intricate web of decentralized IP links built upon many of the routing features first employed by earlier packet radio networks [4]. Borne from a heritage of 1960s and 1970s packet data radios designed to provide reliable communications for connectionless, non-real-time traffic, today's mesh networks have evolved to provide multicast IP traffic with real-time requirements [1]. In essence, mesh networks extend the concept of packet data radio communications by using sophisticated digital modulation schemes, traffic routing algorithms, and multi-hop architectures that challenge the laws of physics by using minimal transmission power to increase data throughput over greater distances. With mesh networks, any node within the network can send or receive messages and can relay messages for any one of its hundreds or thousands of neighboring nodes, thus providing a relay process where data packets travel through intermediate nodes toward their final destination. In addition, automatic rerouting provides redundant communication paths through the network should any given node fail [2]. This ability to reroute across other links not only provides increased reliability but extends the network's reach and transmitting power as well. This resilient, self-healing nature of mesh networks stems from their distributed routing architecture where intelligent nodes make their own routing decisions, avoiding a single point of failure. Because mesh networks are self-forming, adding additional nodes involves a simple plug-and-play event [3]. And because mesh networks don't rely on a single access point for data transmissions, users of this technology can extend their communication reach beyond a typical WLAN. Furthermore, mesh networks and their low power, multi-hopping ability allow simultaneous transmissions to reach nearby nodes with minimal interference [17]. Achieving this self-forming, self-healing utopia with minimal power and signal interference involves the implementation of sophisticated routing logic within the software and hardware to account for minimum latency, and maximum throughput, as well as provide for maximum security and reliability [7]. Figure 1 depicts a mesh network configuration with a single wireless access point connected to a wireline backbone that provides end-users with Internet access. If so desired, the four end-nodes could function as a self-forming independent service set capable of sending and receiving voice, video, and data between themselves without a wireless access point.

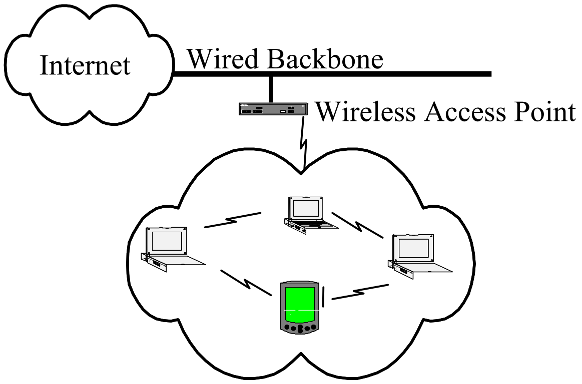

Figure 1. Mesh Network with Single Access Point

As with all radio frequency (RF) communication systems, mesh networks must contend with noise, signal fading, and interference; however, unlike other RF systems, mesh networks deal with noise, signal fading, and interference through an air interface protocol originally designed to provide reliable battlefield communications. Known as quad division multiple access (QDMA), this air interface provides the driving force behind mesh network capabilities. Conceived by Military Commercial Technologies (MILCOM) and a communications division of ITT Industries, QDMA allows mesh networks to facilitate higher throughput without sacrificing range - or extending transmission range without sacrificing throughput. QDMA supports low-power, high-speed broadband access in any sub 10 GHz frequency band, providing non-line-of-sight node linking to dramatically increase signal range without sacrificing throughput. Geared toward wide area mobile communications, QDMA compensates for wild fluctuations in signal strength with powerful error correction abilities and enhanced interference rejection that allows multi-megabit data rates – even from a mobile node traveling at 100 mph and beyond. And with shorter distances between network nodes, the resulting decrease in interference between clients provides for more efficient frequency reuse. Furthermore, QDMA offers highly accurate location capabilities independent of the satellite-based global positioning system (GPS) [2], [4], [5], [6].

2. Commercial Deployments

Since the inception of QDMA and the subsequent commercialized version of this technology, venture capital firms have invested more than $100 million since 2001 for continued design and development of mesh networks that could ultimately compete with IEEE’s 802.11b [3]. One firm, appropriately named MeshNetworks, has adopted the QDMA technology with direct sequence spread spectrum (DSSS) modulation in the 2.4 GHz industrial, scientific, and medical (ISM) band, providing 6 Mbps burst rates between two terminals. Backed by almost $40 million in venture funding from 3Com Ventures, Apax Partners, and others, MeshNetworks signed its first customer, Viasys Corporation, in November 2002. Eventually, MeshNetworks plans to offer their networking capability in the 5 GHz unlicensed national information infrastructure (UNII) band [8]. For now, MeshNetworks, headquartered in Maitland, Florida, is testing a 2.4 GHz prototype in a five-square-mile test network around its Orlando suburb with an FCC experimental license to build a 4000-node nationwide test network [6]. To maintain Internet connectivity, MeshNetworks relies on multi-hop routing between nodes mounted on buildings, light poles, vehicles, and end-user devices [17]. Aside from designing prototype routers, relays, and PDA-size client devices, MeshNetworks plans to offer a software overlay solution for 802.11b clients in existing networks, effectively extending the range and link robustness of existing Wi-Fi networks through mesh-style multi-hopping [6]. Furthermore, MeshNetworks recently announced a deal with auto-parts manufacturer Delphi to test the feasibility of mesh networks in a telematics environment [9]. MeshNetworks competitors include FHP Wireless, which recently announced its formal launch date in March of 2003, and Radiant Networks from Cambridge, U.K., which has deals in place with British Telecom, Mitsubishi, and Motorola [3].

Interestingly, each of these potential mesh network providers will face a similar network coverage dilemma, a sort of catch-22 where the ability to expand network coverage hinges on the deployment of new subscribers whose mobile nodes will act as router/repeaters for other nodes. In this scenario, requirements for expanded coverage dictate the need for more subscribers – but the service provider can’t solicit new subscribers until the coverage extends to the new subscribers’ area. To resolve this, MeshNetworks and Radiant Networks supply ‘seed nodes’ mounted on telephone poles or streetlights for initial coverage and redundancy with the level of required seeding determined by specific business objectives [10], [12].

3. Military Perspective

Aside from efforts to tame mesh network technology for commercial deployment, the U.S. Government has spent significant time, money, and resources on the research, development, and field deployment of mesh networks for tactical military operations. With any mesh network deployment, the addition or deletion of network nodes can alter the dynamic network topology, emphasizing the need for efficient network organization, link scheduling, and routing to contend with varying distance and power ratios between links. A military environment, however, imposes additional complications by enforcing low probability of intercept and/or low probability of detection requirements, which in turn pose stringent power and transmission requirements on every network node [4].

Tactical military operations must also contend with varying degrees of mobility that occur within the military’s echelon of four Divisions per Corp, four Brigades per Division, three Battalions per Brigade, four Companies per Battalion, and three Platoons per Company [13]. In this particular hierarchy, the often unpredictable nature of battle can dictate the need to merge and reconfigure sections of missing forces, disrupting the communication paths from node to node within Battalions, Companies, or other command structures. And while some engineers argue that alternatives to mesh networking exist to support communications in these battlefield conditions, others highlight the mesh network capability for instantly configurable, decentralized, redundant, and survivable communications in frontline battle areas or during amphibious or airborne operations where a clustered, ad hoc network configuration might consist of people, planes, ships, and tanks. In this military environment, mesh networks must contend with the military's requirement for preservation of security, latency, reliability, intentional jamming, and recovery from failure [1], [4].

The Joint Tactical Information Distribution System (JTIDS) provides one example of a repeater-based, full mesh military network architecture that uses airborne relay to perform base station functions such as routing, switching, buffering multiple packet streams, and radio trunking. Developed for air-to-air and air-to-ground communications, JTIDS consists of up to 30 radio nets each sharing a communications channel on a time division multiple access (TDMA) scheme with most nodes in the network containing minimal hardware and processing power. In this configuration, the loss of any node within a radio net would have no negative impact on communications connectivity [1].

In another example, the Army's Communications Electronics Command oversees ITT Industries' development of the Soldier Level Integrated Communications Environment (SLICE). Designed for voice communications and troop mapping functions, SLICE represents the latest in military mesh network capabilities. Originally conceived as the DARPA Small Unit Operations Situational Awareness System, SLICE supports simultaneous networking of voice, video, and data transfer with a waveform and media access protocol that yields effective communications in urban canyons and dense jungle environments. In its present form, SLICE consists of a backpack-size computer with a headset display and built-in microphone. By 2005, ITT expects SLICE to shrink to the size of a PDA. With respect to SLICE, JTIDS, or any other military radio architecture, the theme of digitized battlefield communications describes the war fighter landscape with requirements for wearable, ruggedized personal computers capable of flawless performance under harsh conditions [14], [15, [16].

4. Final Thoughts

With low transmission power requirements and a multi-hop architecture, mesh networks increase the aggregate spectral capacity of existing nodes, providing greater bandwidth across the network. And since mesh networks transmit data over several smaller hops instead of spanning one large distance between hops, mesh network links preserve signal-to-noise ratios and decrease reliance on bandwidth-pinching forward error correction techniques [17]. In terms of scalability, mesh networks can accommodate hundreds or thousands of nodes with control of the wireless system distributed throughout the network, allowing intelligent nodes to communicate with one another without the expense or complication of having a central control point. Furthermore, these networks can be installed in a manner of days or weeks without the necessity of planning and site mapping for expensive cellular towers. As with other peer-to-peer router-based networks, mesh networks offer multiple redundant communications paths, allowing the network to automatically reroute messages in the event of an unexpected node failure. Thanks in part to standards efforts underway in the Internet Engineering Task Force (IETF) MANET Working Group, the design and standardization of algorithms for network organization, link scheduling, and routing will help facilitate the commercial acceptance of mesh network technology.

Despite their potential to provide a more sophisticated WLAN alternative, mesh networks must effectively address security issues with end-device and router introduction, user data integrity, device control and authentication, and network authentication. Aside from security issues, the RF-independent, self-forming, and self-healing characteristics these networks display come at the expense of complex and power intensive computer processing. Even in static environments with all nodes stationary, mesh network topologies remain dynamic due to variations in RF propagation and atmospheric attenuation. With mobile nodes, a mesh network's constantly shifting topology dictates the need for dynamic routing allocation, resource management, and quality of service management – all of which must be precisely choreographed to ensure optimum performance and reliability. Other skeptics contend that as ad hoc multi-hop networks grow, performance tends to deteriorate due in part to excessive traffic control overhead required to maintain quality of service along a path with multiple hops besieged by inconsistencies in routing and connectivity as nodes are added and dropped. Also, the network must handle multiple access and collision problems associated with the broadcast nature of RF communications. Regardless of these technical hurdles, researchers at Intel continue to push the research and development envelop in an effort to design a 100 Mbps mesh network where every network element (PC, PDA, mobile phone, etc.) could act as a data relay and link itself to all the devices in an intelligent network [10], [12], [17], [19].

With the ability to deploy a wide-spread coverage network without towers, mesh networks pose a viable alternative to traditional cellular architectures. Labeled as a potentially disruptive fourth-generation technology, QDMA-based mesh networks aren't alone in their quest for the ultimate radio communications system capable of operating in unlicensed spectrum. Though technologically disparate from QDMA-based networks, ultra wideband (UWB) mesh networks present one alternative to MeshNetworks, Inc. proprietary QDMA-based software, thanks in part to recent FCC rulings approving limited usage of UWB devices. Several companies are championing the development of UWB networks, which promise data rates of 100 Mbps at very low power levels over a wide bandwidth from 1 to 10 GHz. By employing time-modulated digital pulses in lieu of continuous sine waves, mesh networks with UWB technology can send signals at very high rates in wireless communication environments that suffer from severe multipath, noise, and interference. Whether UWB mesh networks or QDMA-based mesh networks will prevail remains to be seen. Some analysts give the edge to UWB as an open standard, which is steadily gaining support in commercial and military markets. Either way, the continued development of mesh networks for military and commercial markets holds promise for a radical shift in the way we view the world of wireless communications [18], [20].

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