Optimizing Routing for Fully-Wireless Multi-Hop Networking

The advantages for fully-wireless routing are clear but unfulfilled. Physical infrastructure remains the most significant cost of any new outdoor installation. Solar-powered solutions exist, but are both costly and short-range because of two primary (and sometimes conflicting) factors: power consumption and typical throughput loss-per-hop nearing 50%. This drawback is not a concern for a three-AP home mesh network, but is unsuitable for larger networks. However, due to advances in both mobile computing and advanced routing techniques, it is now possible to build expansive WiFi networks that do not rely on a wired backhaul, or even a power grid.

The limiting factor in many ad-hoc ("mesh") networks is the overhead routing packets overflowing and overcrowding receive buffers [2]. Frequent reorganization of the network and lack of synchronization causes significant losses at more than 2-3 hops away from the central internet access point. The amount of overhead can increase geometrically with the number of nodes, severely limiting the maximum network size. Commercially, the self-healing and automatic nature of mesh networks has been eclipsed by their speed and reliability problems. Today many commercial "mesh" networks are actually static, self-assembling networks that are not able to redistribute resources or self-heal in a reasonable amount of time.

There are two primary categories of mesh/ad-hoc networks: reactive and proactive. Reactive routing reorganizes the route with each packet, calculating the ideal route at the time of sending. These networks cover dynamic spaces very well, but have scalability issues as the entire network typically needs to be flooded with updates with each new packet.

Proactive routing uses historical characteristics to predict the best route for a packet to take. These networks require a lot of data to be stored on the network and do not always choose the optimal route, but the overhead is a smaller portion of the total throughput and typically has a reconfigurable refresh time. Proactive networks are great for semi-static conditions and have been popularized for community networks.

Traditionally, IEEE 802.11 wireless routing is done on the Network layer. Hardware packet processing on the Data and Link layers allows for simple IP-table based routing. However, for a packet to be routed, many layer translations are necessary at each node. 802.11s, the IEEE standard for mesh networking, operates on the Link layer adjacent to the Physical radio layer. Link-layer networking is more similar to the operation of a managed ethernet switch than a wireless router. This allows packets to be routed without significant translation and enables "blind" nodes to operate without knowledge of a full IP table, just a distance vector described below. The popularity of this standard has enabled soft-processing of packets in available network accelerator drivers. IEEE 802.11s's hybrid-mesh (partially proactive and reactive) nature carries losses that have since compromised its popularity, but the contribution to link-layer ad-hoc networking has remained and been made available in the Linux stack for custom protocols to be developed.

Ultimately, mesh networks require more processing power than is available on most routers. More substantial architectures designed for mobile phones have recently been modified and made available as internet processors, most notably Qualcomm's IPQ variant on the APQ Snapdragon family of mobile processors, which run most consumer mesh networks [1]. Historically, two primary factors have limited the expansion of mobile technology for routing: lack of demand for low power consumption in wireless routers and the power distribution within typical WiFi hardware. Even today, much of the power consumed by a router is from the radios and network accelerators themselves rather than the processing.

Fig. 1. Ventev PoE+ solar powered system [3]

The result of high-powered routing hardware is fully-wireless systems that weigh over 150kgs and require two 1.5x3m solar panels in support of PoE. Although these devices do not (strictly) require a connection to a power grid or an Ethernet backhaul, they require structural support and cost over $3,700USD [3]. Unfortunately, these cumbersome solutions counteract the benefits of mesh networks and offer slow, expensive service. The alternative of trenching outdoor cables is even more expensive.

Routing and communication techniques in WiFi have traditionally been less efficient than those in the cellular space, due to the lack of vertical integration. Within embedded Linux development, which provides the backbone for most WiFi firmware today, there is a disconnect between device driver engineers and internet protocol experts. Development engineers employed at silicon companies most often have a background in hardware, rather than global internet and routing on a high level [4]. This leads to scalability issues when large-scale data management is applied to unoptimized P2P links.

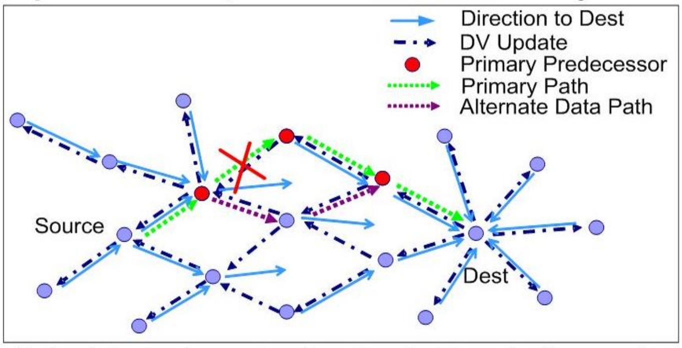

Fig. 2. Distance-vector routing

Following the growth of mobile computing and link-layer availability, advanced routing techniques are taking form in community mesh networks. Network Coding, where two packets are combined and sent out simultaneously for multiple-access, bares resemblance to the cellular Code-Division Multiple-Access (CDMA) protocol. In both, a bitwise exclusive-or reveals the intended message from the same packet sent to multiple recipients with different decoding [5].

Scalability problems in mesh networks can be managed by Distance-Vector routing, which calculates only the "next-node" of a route by combining all possible routes through an adjacent node into a single metric. In a distance-vector routing protocol such as Ad-Hoc On-Demand Distance-Vector (AODV), nodes are blind to the full routing of a packet and therefore do not have hard scaling limits as the size of a network grows. This is in contrast to more established Link-State routing such as Optimized Link-State Routing (OLSR), which calculates an entire route at once. An additional benefit of distance-vector routing is the 'cluster' effect of only considering adjacent nodes, which reduces synchronization problems to 3-7 nodes. Combined with enabling multiple packets to be sent simultaneously via network coding, clustering renders packet synchronization possible within a single cluster through buffering at the central node.

Typically, routing decisions are made based on packet loss or the number of hops. Most of the available data in a network – SNR, RSSI, packet window, encoding, maximum throughput – is not considered for link quality metrics. The reason for this is the complex and often unpredictable relationship these may have in a network, and so most available link data is disregarded to lower the overhead in determining routes.

Fig. 3. Mesh++ solar-powered node (exploded view)

Mesh++ has developed a compact, solar-powered ad-hoc router with preliminary tests demonstrating 17% loss-per-hop using a distance-vector proactive routing protocol and cluster synchronization. With a 700MHz quad-core processor and a redesign of the modern router, advanced distributed routing techniques can be accomplished in a 0.5x0.5m form factor. A hardware cryptography core allows layer-2 data encryption throughout the backhaul network, with authentication at the points of entry. With the use of advanced data aggregation techniques, links are characterized based on many of the metrics available, leading to a more accurate routing decision through distributed machine learning without the scalability problems of centralized self-organizing networks (SONs). A 4x4 MU-MIMO dedicated 5GHz backhaul is able to support high speeds throughout hundreds of acres, while 2.4GHz is reserved for user access. Low-loss routing results in networks that can cover over 17x as much area as standard repeaters or mesh networks at the same speeds.

Network configuration is automatic and nodes do not need to be wired together or connected to a power grid, simplifying and minimizing the cost of installation for large outdoor and temporary networks.

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