Optimal Distance of Multi-hop 802.11 WiFi Relays

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Abstract—After a disaster it is important to repair communication networks as fast as possible to save lives. The survivors can use commodity 802.11 WiFi devices to create a wireless multi-hop network to reestablish communication. The distance between neighboring devices is an important parameter to determine the performance of the multi-hop network. In this paper, we determine the effect of the hop distance on the latency and the data rate of the resulting network.

We use analytical descriptions of signal propagation and data rate to determine the end-to-end performance of the resulting network. We determine the optimal distance for minimal latency and maximal data rate and show that the two optimization goals result in different hop distances.

While the resulting optimal values depend on the scenario parameters, optimizing a network for low latency or high data rate will lead to different placements of relays.

I. INTRODUCTION

After a large scale disaster the communication networks are usually damaged and make communication nearly impossible. We propose to repair communication networks as well as possible without outside help, that is, only with the means available to survivors.

Mobile phones can relay the communication of survivors to a location with internet access. Because mobile phones are ubiquitous in many societies today they are also widely available after a disaster. While they require electrical energy to operate, their batteries will allow them to operate for some time and many possibilities exist to charge them even after a disaster: cars, external battery packs, hydrogen fuel cells, solar panels, hand cranks, and diesel generators.

In this paper we consider the following scenario: survivors in an evacuation area are not connected to the internet, but know a nearby location which provides connectivity. A survivor collects mobile phones which she uses as relays between the evacuation area and the location with internet connectivity. In this paper we analyze how the number of placed phones, and thus their distance, affects the latency and data rate of the resulting network.

II. RELATED WORK

Portmann and Pirzada [1] explain the requirements for a disaster recovery network and Quang et al. [2] describe how a 802.11 WiFi multi-hop network can be implemented. While these approaches focus on the networking, we analyze different placements of the devices which form the network.

Lee et al. [3] show how multi-hop relaying can increase the performance of a wireless network. In contrast to our case they opportunistically use present equipment and do not consider the problem where to place the devices.

Chattopadhyay [4] describe how to place relay nodes for maximum data rate. However, their model assumes any device overhearing a packet can relay it, which is not the case using WiFi networks. This means that their model cannot be applied in our case.

III. MODEL

We model \( n + 1 \) devices placed in a straight line of length \( x \) in an open environment with a distance \( d = x/n \) between neighboring devices (see figure 1). We assume each device creates a 802.11g WiFi network for its child to connect to and connects to the network of its parent and uses network address translation to forward the packets from its child to its parent. Our goal is to determine the optimal number of hops and, thus, the optimal distance between relay devices. To determine the quality of the connection we use the metrics latency \( L \) (round trip time in ms) and data rate \( D \) (throughput in bit/s).

We model the received signal strength \( S \) of a single wireless hop using the free space path-loss model with the path-loss exponent \( \alpha \) and the transmit power of the transmitter \( P_t \). We do not include any antenna gain as we assume omnidirectional antennas. To determine the resulting data rate \( D_S \) with the signal strength \( S \) we use the Shannon-Hartley theorem and reduce the resulting data rate by a factor of \( I \) to compensate for the inefficiency of WiFi compared to the theoretical limit:

\[
S = P_t \left( \frac{\lambda}{4\pi d}\right)^\alpha, \quad D_S = \min(D_{\text{max}}, IB \log_2(1 + S/N)),
\]

where \( \lambda \) is the wavelength, \( N \) the noise power, and \( B \) the bandwidth. Additionally, we limit the maximum data rate to the maximum data rate of 802.11g WiFi \( D_{\text{max}} = 54 \) Mbit/s.

We determine the time \( L_S \) a single hop of wireless transmission takes from the constant overhead \( R \) per transmission and the time it takes to transmit the packet of size \( P \). We assume the end-to-end latency \( L \) to be equivalent to \( n \) single-hop transmissions. We determine the end-to-end data rate \( D \) under the assumption that all \( n + 1 \) nodes share a single wireless collision domain, that is, only one node can transmit at a time and the medium sharing is perfect:

\[
L_S = R + P/D_S, \quad L = nL_S, \quad D = D_S/n.
\]
Fig. 2. The number of relays to achieve the lowest latency depends on the total distance that needs to be covered.

Fig. 3. The number of relays to achieve the highest data rate depends on the total distance that needs to be covered.

IV. RESULTS

Next we present the results obtained by evaluating the equations presented earlier using the parameters: \(\alpha = 2.8\), \(c = 299792 \text{ km/s}\), \(\lambda = c/2.4 \text{ GHz}\), \(P_t = 30 \text{ mW}\), \(B = 20 \text{ MHz}\), \(N = -90 \text{ dBm}\), \(I = 1/7\), \(P = 1500 \text{ Byte}\), and \(R = 1 \text{ ms}\).

We consider a scenario in which two devices are placed at a distance of \(x\) and compare the performance when they are connected by 1, 2, or 3 hops. Figure 2 shows the resulting end-to-end latency and figure 3 shows the end-to-end data rate.

In our model the optimal (regarding both latency and data rate) hop distance \(d\) is independent of the total distance \(x\) to cover. To determine the optimal hop distance \(d\) we normalize the latency for a given hop distance \(d\) per meter. This allows us to compare the resulting latency of different hop distances independent of the total distance. The minimum shown in figure 4 is, thus, also the hop distance \(d\) at which the end-to-end latency is minimal. It can be calculated by multiplying the \(y\)-value with the total distance \(x\).

We determine the optimal hop distance \(d\) for data rate analogously with the difference that the \(y\)-value is the product of data rate \(D\) and hop distance \(d\) instead of their ratio as the data rate will decrease with distance and not increase as latency does. To calculate the end-to-end multi-hop data rate from figure 5 the \(y\)-value has to be divided by the total distance \(x\). We conclude that optimizing this network for minimal latency or maximal data rate results in different hop distances.

V. CONCLUSION

We used a model based on free-space propagation path-loss and the Shannon-Hartley limit to model a scenario of 802.11g WiFi multi-hop communication. Using a set of realistic parameters, we analytically determined the optimal distance between relay nodes to minimize latency and maximize data rate. While the actual results depend on the parameters we showed that they differ when optimizing for minimal latency or maximal data rate.

REFERENCES