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# Is the unlicensed band “good enough” to deploy a muni Wi-Fi network without mesh infrastructure?

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## Abstract

We explore a municipal mesh networking architecture called SocialMesh that can be built entirely from end-user devices (analogous to amateur radio, HAM, and CB-radio), without requiring dedicated infrastructure mesh nodes, cell base stations, or spectrum licenses. Compared to using Wi-Fi for mesh backhaul, our estimates show it may be possible to achieve up to 10x more coverage area and reliability, and operate 10x faster using SocialMesh to backhaul Wi-Fi client connections. This implies a minimum end-user device density of a few per square mile or less and it can scale up to support much higher densities of several thousand per square mile. This is ideal for increasing the connection probability in challenging RF environments, and extending battery life for handheld devices by an estimated factor of 10x. Open design specifications for SocialMesh will be updated at http://www.socialmesh.org. Question to members of the amateur radio community: Is there any experience and lessons learned from the operation of global and wide-area amateur radio networks that may be applied to the unlicensed band infrastructureless network? Please contact the authors with your advice and suggestions.

## Introduction

During the past few decades, municipal mesh networks operating in the unlicensed band have become widespread throughout the world. In the 1990s, Metricom deployed some of the earliest unlicensed mesh networks in several major metropolitan areas using mesh nodes deployed on lampposts -- these did not use Wi-Fi. During the 2000s, several hundred cities, large and small, were able to deploy their own municipal mesh networks based entirely on commercially available W-Fi chips using light-pole mounted infrastrcuture from Tropos [1], Belair, and others. Examples include Chaska, Mountain View [8], and Oklahoma City.The unlicensed municipal Wi-Fi networks have several unique advantages not possible with any other technology. Not only do they provide contiguous Wi-Fi coverage for end-user devices across the city like licensed cellular systems, the city can decide to create its own low-cost broadband alternative for residents, bridge the digital divide, provide data access for municipal workers, securely serve data for public safety applications, and connect its meters and sensors. The resilient and rapidly deployable properties of mesh networks provided public access communications after disasters such as 9/11 (Metricom Network) and Hurricane Katrina (Tropos) when virtually all other communication infrastructures were not operational for days or weeks after the disaster.

Despite the widespread use of municipal Wi-Fi mesh networks, they have several barriers to adoption that relate to the placement of infrastructure mesh nodes:

1. The Wi-Fi radio standard is limited in outdoor connection reliability compared to cellular connections which can connect at much lower signal levels. The density of infrastructure mesh nodes for supporting standard low-power Wi-Fi client devices (like smartphones) typically ranges from 10-100 per square mile ([5], [6], [7]) depending on several factors most notably the transmit power of the client device and the type of terrain (trees, hills, desert, etc).
2. In addition to the investment for client devices themselves, the large density of infrastructure nodes required makes municipal mesh networks costly for cities to deploy from a financial standpoint. While typically half the cost of a comparable cellular network, the upfront capital expenditure (CAPEX) for a muni mesh network is in the range of hundreds thousand dollars per square mile. While less costly than cellular, a muni mesh network also requires a significant operational expenditure (OPEX) to maintain over time.
3. Even in cases where there is widespread public demand for muni Wi-Fi networks, they can encounter resistance from local telecommunications incumbents [2] as well as face hurdles in approval from city councils for securing mounting assets for the infrastructure nodes.

End-user devices include mobile devices like Wi-Fi laptops, tablets, smartphones, and fixed devices called customer premise equipment (CPE). In a typical municipal Wi-Fi deployment, between 5-30% of the city's residents of cities would obtain a fixed CPE that is continuously powered by their wall outlet to access the mesh infrastructure. For example, chaska.net observed a 20% household penetration within one month of the network being operational and achieved greater than 28% subscriber take-rate after the service was operational for about two and a half years [3]. Can a reliable and scalable network be built using end-user client devices operating in the unlicensed band without infrastructure mesh nodes?

## SocialMesh

The ideal solution to overcome these problem mentioned in the previous section is a wireless mesh network that does not rely on any infrastructure nodes, but instead is composed almost entirely on end-user client devices (CPEs). These devices can serve a dual purpose as Wi-Fi access points and mesh routers to connect to backhaul at the same time. People can have these devices in their homes (like amateur or HAM radio) or embedded as part of their mobile devices and smartphones (like CB-radio). If it could be built, it would also be deisgned to be much more resilient to any physical or network failures than any network relying on infrastructure during a disaster. It can operate at much lower cost -- requiring minimal or zero CAPEX and OPEX because the infrastructure costs are eliminated. For the reasons similar to why Wi-Fi clients require a municipal mesh, standards-based Wi-Fi devices are unlikely to be able to form a mesh themselves over the area of a typical municipality. The enabling technology is just becoming feasible to experiment and demonstrate a municipal mesh of end-user devices using software defined radio.

The SocialMesh mesh radio architecture has been recently proposed in an article published in IEEE Communications Magazine [4] based on uncoordinated/distributed direct-sequence spread spectrum. SocialMesh is designed to provide maximum connection probability, reliability, and performance to end-users in the presence of the most unfavorable RF conditions possible including obstructions, hostile jamming, in-network interference, and protocol attacks. In the remainder of this paper, we compare the receiver performance, reliability of SocialMesh radios to Wi-Fi radios operating within unlicensed spectrum to evaluate the feasibility of a radio that can support “device as infrastructure” municipal mesh. Assuming an equivalent transmit power for both SocialMesh and Wi-Fi, the receiver performance will determine the relative difference in range, speed, and connection probability.

Communication radios in handheld devices tend to operate at roughly 100 milliwatts for both optimal battery life and affordable cost. Any increase in transmit power beyond 1 watt (1000 milliwatts) tends to incur a disproportionate drain on the battery reducing battery life or increasing the requirement for a physically larger battery, as well as an increase in cost for RF hardware beyond the reach of consumers. Likewise an increase in speed of communication (Mbps) can enable new applications demanding higher data rates (e.g. video) or equivalently increase battery life by conveying the same payload in a shorter time draining less energy from the battery. In general, both faster and lower transmit power is better for handheld devices with fixed battery life or cost.

Wi-Fi radios are designed to operate in 20 MHz of spectrum as part of the 80 MHz ISM band (2.4-2.48 GHz for 802.11g), as well as the 800 MHz UNII band (5-5.8 GHz for 802.11a). Signal propagation differs between these two bands, but the receiver sensitivities for 802.11g (2.4GHz) and 802.11a (5GHz) radios themselves are very similar. 20MHz of unlicensed spectrum is also available in the 900 ISM band (900-928 MHz). As described in the IEEE paper, SocialMesh radios can operate in any channel bandwidth from below 1MHz to as high as 500 MHz depending on the need. First we compare Wi-Fi radios to SocialMesh operating in the same spectrum.

### Wi-Fi versus SocialMesh In Unlicensed Spectrum

Receiver sensitivity is the amount of signal power from the transmitter that is required at the receiver in order to communicate successfully. If we think of a transmitter as a faint light bulb in the distance and the receiver as our eye, receiver sensitivity is like the faintest amount of visible light our eyes can discern the light bulb with. As we move away from the bulb our ability to see it disappears after some point. The receiver sensitivity of our eye is the power of the light at that point where we can barely see it.

Receiver sensitivity can be measured or predicted for each radio as a function of the desired transmission rate. The 802.11g and 802.11a standards for Wi-Fi specify transmission rates from 1, 2, … 36, 54 Mbps and beyond. The radios will perform to corresponding receiver sensitivities. Any antenna improvements such as MIMO can be modeled as improvements in the received signal and apply equally to both Wi-Fi and SocialMesh. In the following two charts, we plot the data rate achievable with SociaMesh radios compared to typical Wi-Fi radios at each received power level.

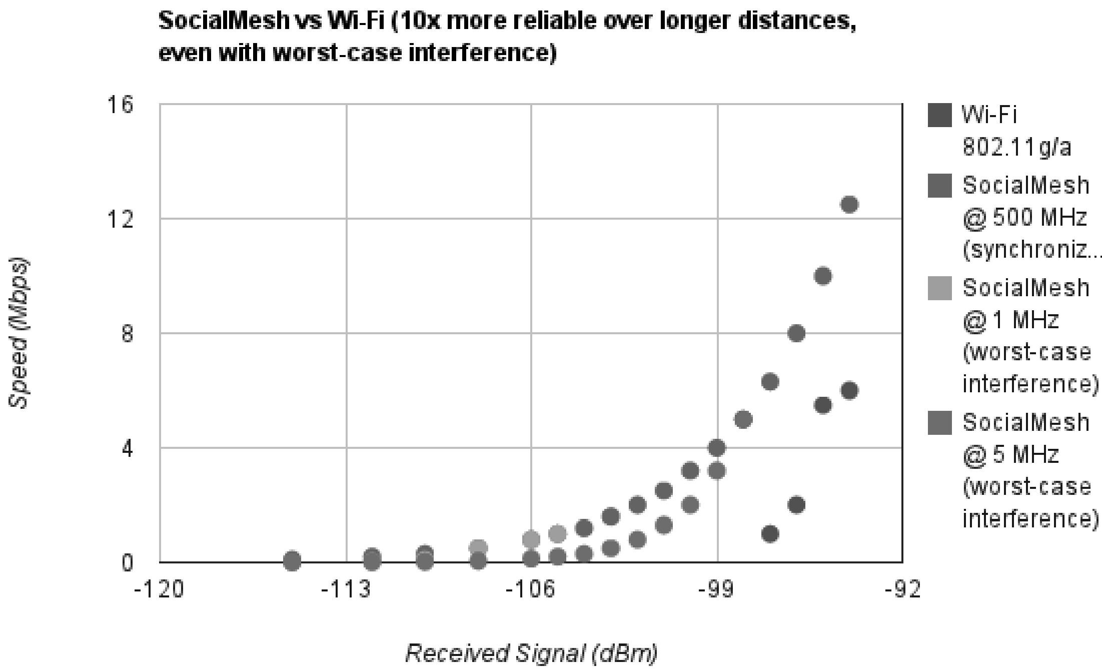



Figure 1

Figure 1 shows that SocialMesh can achieve 10x more coverage area and reliability compared to Wi-Fi, especially in hard to reach situations because it can successfully transmit data -- at much higher speeds in several instances -- when Wi-Fi is unable to connect. This is not entirely unexpected since cellular data radios (3G, etc) routinely perform a similar feat in licensed spectrum. This holds true both with when SocialMesh radios are synchronized to minimize in-network interference, as well as when the radios are subject to worst-case interference either from in-network or external sources. In comparison, Wi-Fi is not designed to provide maximum tolerance to general unlicensed band interference, and instead relys on CSMA/CA to coordinate with other Wi-Fi transmissions at short range.

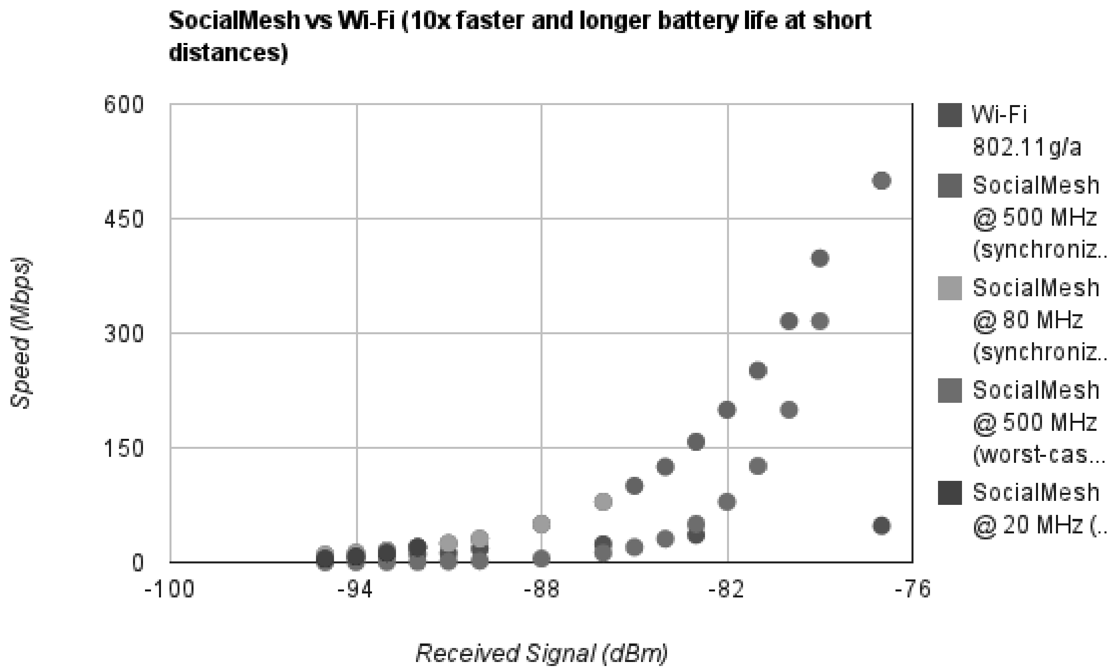



Figure 2

Figure 2 shows that SocialMesh is able to transmit data 10x faster than Wi-Fi when the radios are close enough that received signal is large (>-80 dBm). Much higher speeds can be achieved because SocialMesh can operate in large bandwidth at 500 MHz. Even at 80 MHz bandwidth, SocialMesh can operate at speeds 2-3x faster than Wi-Fi.

## SocialMesh: speed vs distance vs interference (3-d plots)

Using the methodology explained in the IEEE paper [2], in Figures 3-6 we model the data rate performance for a SocialMesh link with transmitters at (100 mW and 1000mW) and a path loss exponent of n=3 for a 20MHz channel at the 2.4GHz and 900MHz unlicensed bands. All interference is assumed to be unsynchronized for the purposes of modeling. In all plots below the two horizontal axes represent the respective distances of the SocialMesh transmitter and a constantly transmitting interferer in the unlicensed band (including other SocialMesh transmitters) in meters, and the vertical axis represents the speed in kilobits per second.

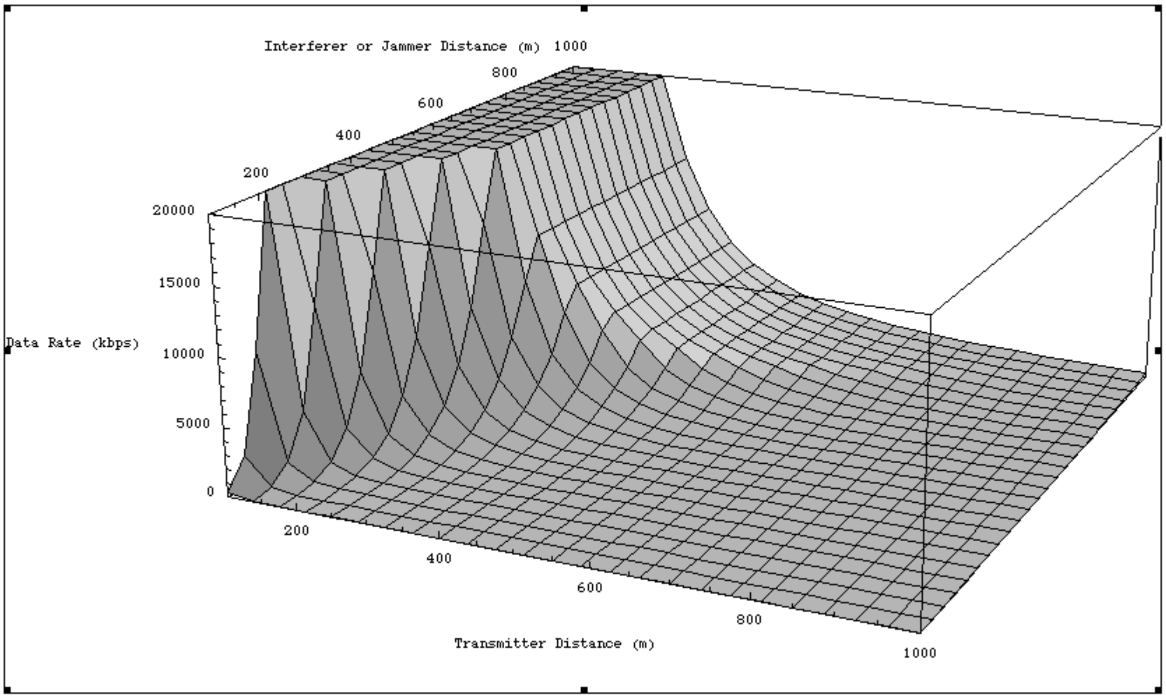



Figure 3

Figure 3 shows that distances of half a kilometer (1/3 mile) can be achieved at megabit per second speeds when the nearest interferer is further away than the transmitter. At shorter distance much higher speeds can be achieved (multiple megabits per second) like Wi-Fi.

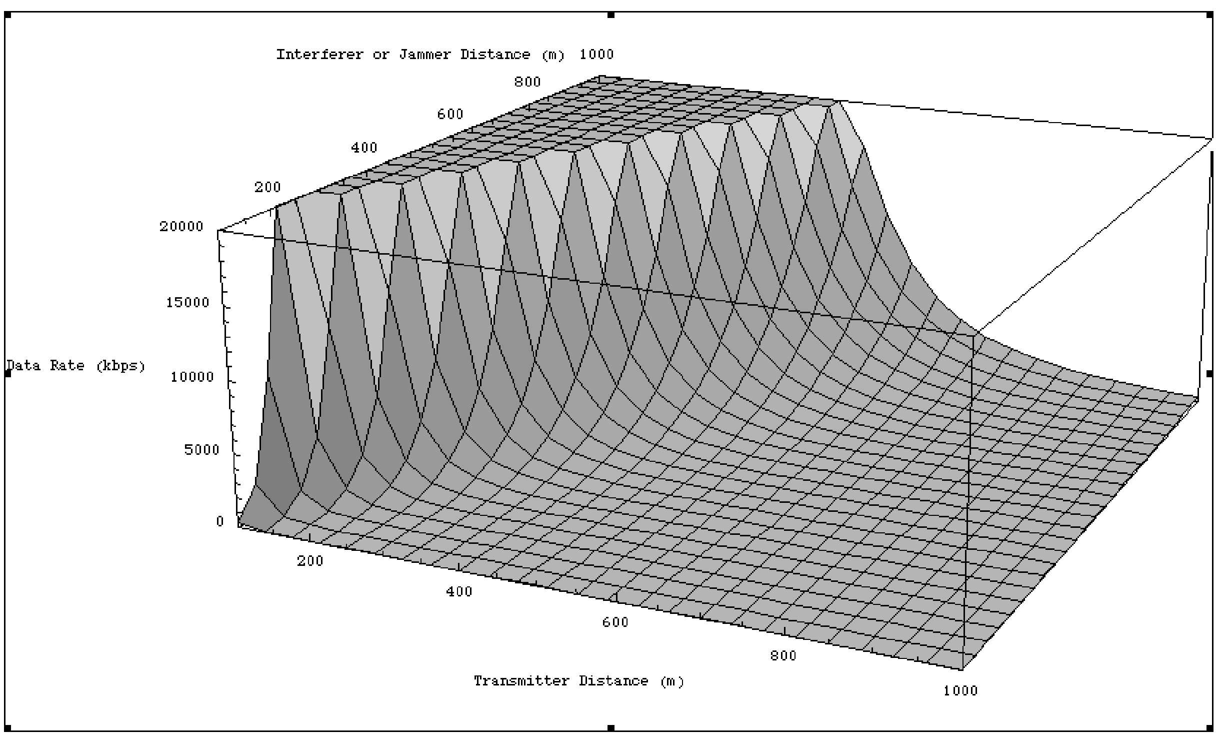



Figure 4

Figure 4 compares the performance of 2.4GHz versus 900MHz using the same assumptions as in Figure 3, except factoring in reduced path loss in 900 MHz unlicensed band. This considerably improves the performance of the link when the interferer is further away, and improves propagation through foliage, hills, buildings/homes and other obstructions. The improved propagation at 900MHz means that the impact of interference from other SocialMesh nodes will be more pronounced as well.

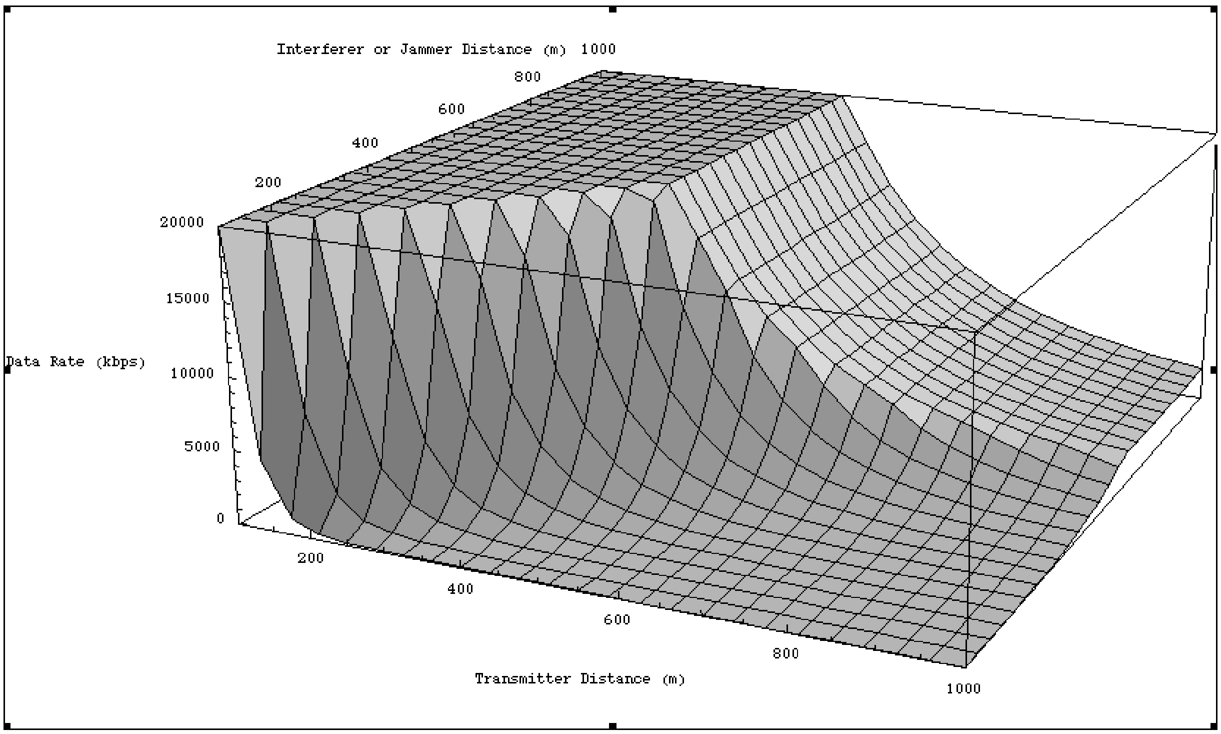
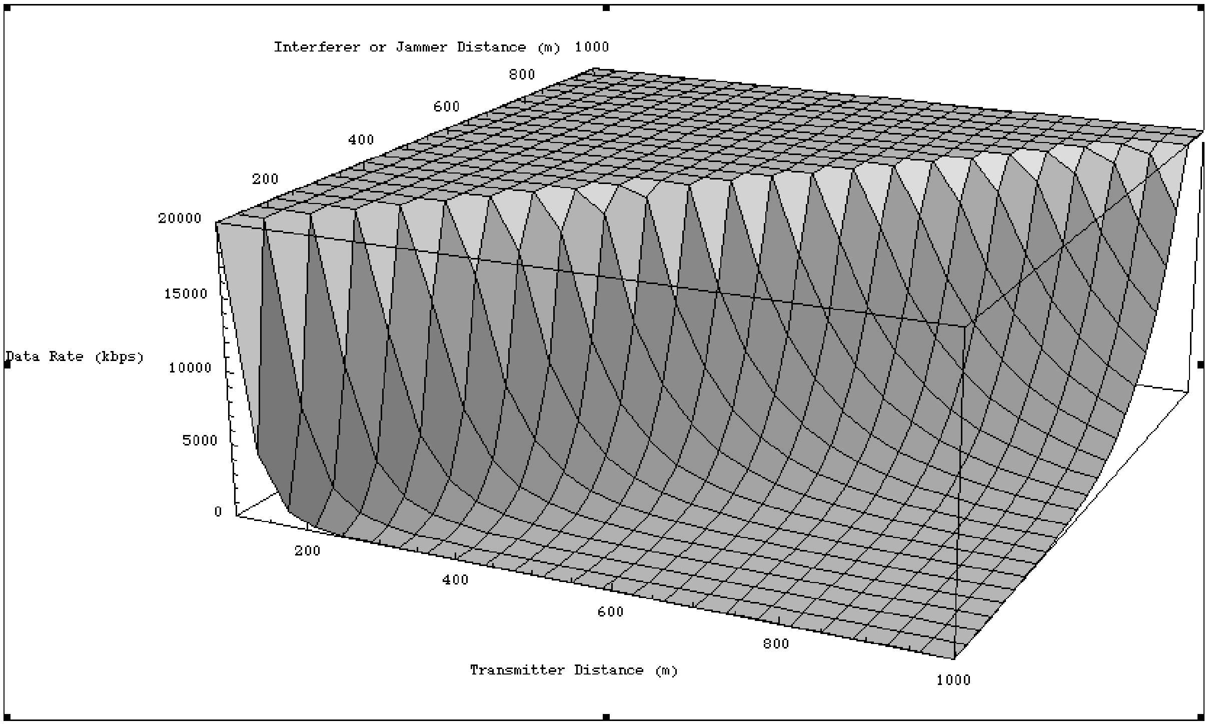



Figure 5

In most typical municipal networks, the mesh nodes are not transmitting 100% of the time as data access is requested by clients in bursts. If we relax the assumption that the neighboring interferers and SocialMesh nodes are constantly transmitting, then the performance of the network improves dramatically. This can be seen in Figure 5 where the interfer is assumed to have a 10% active duty cycle at 900MHz, and the data rate uniformly increases throughout the entire graph (versus 100% duty cycle in Figure 4).




Last but not least, we model what happens to the link when the transmit power is increased to 1W (1000 mW) in Figure 6. This creates a much stronger link compared to Figures 3-5 in the region where the interferer is further away than the transmitter allowing for megabit communication at over 1km and further away and gracefully falling back to low-speed communication at multiple kilometers distance. Such a 1W transmitter may not be practical for mobile nodes, but it can work well for fixed CPE devices provided the cost of the device remains affordable to consumers.

## Node Density for SocialMesh in unlicensed muni applications

By eyeballing Figures 3-6 we might estimate the required node density for the SocialMesh to connect is at most one node every ⅓ mile (half kilometer) at megabit per second speeds. However this is too conservative. The SocialMesh radio architecture is designed to scale down to much lower speed at which the connection range will be well over 1km as shown in these same plots. In situations where external interference from unlicensed band is not a significant factor and interference from SocialMesh nodes dominates, further improvements to link capacity and range can be achieved with narrower bandwidth channels instead of 20MHz (e.g. 1MHz) and by synchronizing the spread-spectrum transmissions to minimize interference. Therefore the minimum node density for SocialMesh to connect is estimated to be well under a few per homes or customers square mile, and maximum is several thousand per square mile in densely populated areas.

## Conclusion

The potential exists for an municipal mesh network to be constructed entirely from end-user devices such as fixed customer premise equipment and mobile smartphones -- without infrastructure mesh nodes -- using the 900MHz, 2.4GHz, and 5GHz unlicensed bands. It requires a minimum end-user device density of less than a few per square mile and it can scale up to support much higher densities of several thousand per square mile in densely populated urban areas. To realize this in practice, radios will have to be adapted to going well beyond the capabilities of the current Wi-Fi (802.11) standard. The increasing availability of software defined radios such as GNU radio and other platforms is likely to open up the full potential of radios operating in the unlicensed band over the long-term. Open design specifications for SocialMesh will be updated at http://www.socialmesh.org. Question to members of the amateur radio community: what lessons can be learnt from the operation or amateur radio networks that may be applied to a metro-scale or global infrastructureless network comprised of only end-user devices? Please contact the authors with your advice and suggestions.

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