RightMesh

The **Power** of **Connectivity** in the Hands of the **People**

Decentralized Mobile Mesh Networking Platform.Using Blockchain Technology and Tokenization.

rightmesh.io

TECHNICAL WHITE PAPER

March 9, 2018	5.0
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This is the FINAL document prior to the RightMesh Token Generating Event (TGE)

This document constitutes a description of the RightMesh platform and the functionality of the RightMesh RMESH tokens; it is for informational purposes only and may change as the RightMesh technology develops over time.

Technical White Paper:
A Decentralized Mobile Mesh Networking Platform Powered by Blockchain Technology and Tokenization

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Change Log

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Dec 4, 2017	V. 2.0	Updated the Token Model, Added Networking Details, Added some basic assumption calculations	JE
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1.Introduction

This technical paper is intended as a supplement to the *RightMesh White Paper* (*http://www.rightmesh.io/whitepaper*), which more broadly provides an overview of the opportunity for RightMesh and the RightMesh Token Generating Event. This technical white paper gives more details and assumes in-depth knowledge of complex systems, networking, encryption, and cryptocurrencies. Throughout each section, the general high-level architecture is presented, along with justifications for design decisions. Our progress to date will be presented, and areas where future work is required will be specified in each section. We will conclude with a summary of the ongoing technical roadmap which we believe helps to support the original paper.

The document makes the technical case for a tokenized, mobile mesh network where the devices are mostly smartphones, IoT devices, sensors, automobiles, and other devices that have had difficulty connecting traditionally since they may move into (or exist in) parts of the world that are connected to infrastructure poorly--and are likely to remain as such for some time. The token system is designed to incentivize devices and people to join a network, stay within a network, and act as virtual infrastructure. It has been designed so that it can work immediately in today's cryptocurrency environment. That is, the system operates under the assumption that smartphones are still not capable of participating as full crypto nodes. At the same time, decisions to "future proof" the technology have been made with the assumption that this will not always be the case.

2. Technology Overview

This section aims to make the case for why mobile wireless mesh networks are important and distinctly different from infrastructure networks from a technological perspective. It compares other network architectures, identifies shortcomings, and outlines how a mobile wireless mesh might improve and enhance infrastructure based networks and architectures. First, an explanation of how most existing devices, apps, and services communicate is provided. This is framed within a discussion of centralized vs. decentralized services. There is also a brief overview of why not all p2p services and networks are decentralized enough (i.e., reliant on infrastructure or not). This discussion provides an overview of why the status quo is a

problem. Next, an overview on the different relevant architectures is provided so that it is well understood by the reader what exactly a mobile wireless mesh network is, and how it is different from other similar networks. Finally, the section is concluded with an overview on the RightMesh core technology in the context of all of this background on network architectures.

Centralized Architectures vs Decentralized Application Architectures and the Networks each depends upon

The apps and services which run on top of networks have evolved to take advantage of fast, reliable and expensive infrastructure. Consider typical chat applications today like Facebook Messenger, Slack, Google Chat, etc. Assume two devices in the same room wish to have a chat with each other using one of these apps. Suppose both phones are using the same Wi-Fi network (Fig. 1). The data from the first phone will travel from the phone, to the Wi-Fi network, to the regional Internet Service Provider (ISP), through potentially several routers on the internet as traffic moves from the regional network to the Internet backbone (Tier 1) (fibre lines, undersea cables, etc.) until it reaches an Amazon Web Service (AWS), Google Cloud, or Azure server. In this server, the other phone user is looked up, and the message is relayed back in the same direction as it originally came from, until it reaches the same Regional ISP and Wi-Fi network that the data first originated from. Then, it is sent to the second phone. If the ISP agreement doesn't provide unlimited data plans, the data was essentially paid for twice: once to be sent and once to be received.

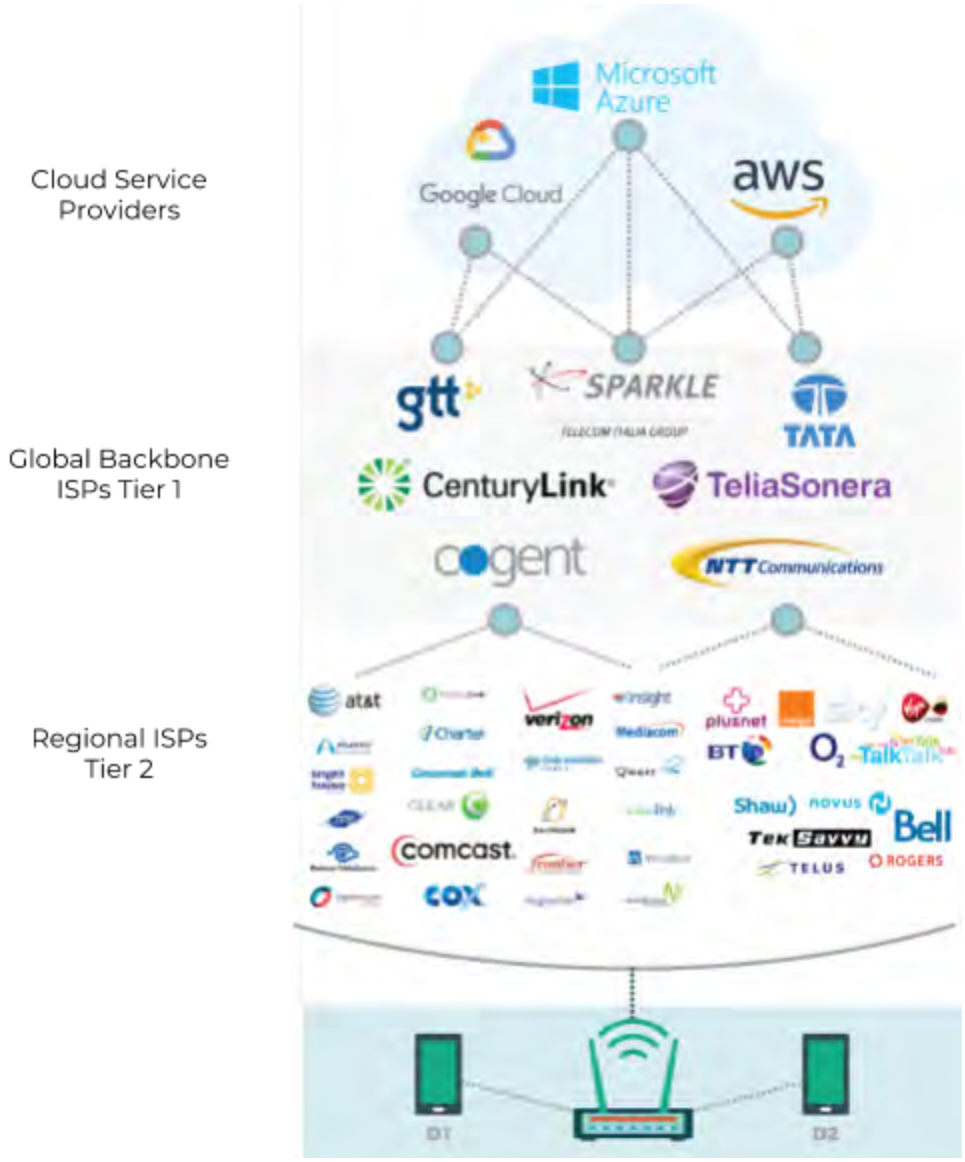


***Fig. 1**: The path data takes to get from one device to another with traditional messaging apps.*

Consider the same two phones, but one phone is now on the cellular network (Fig. 2). Typically cell phone data is more expensive per-byte than home or business Internet. Everything in the first example is the same except perhaps the ISP is different, and the phone using the cell phone data is paying more money. The reason it is probably more money is because there is a fixed amount of wireless spectrum, and it is not possible to just add more spectrum like it is possible to just add more fibre lines (although you can deploy smaller and smaller cells). The only real change from Fig. 1 and Fig. 2 is the attachment point has changed slightly. The two connections may now be using two different regional ISPs so the return path may be slightly different.

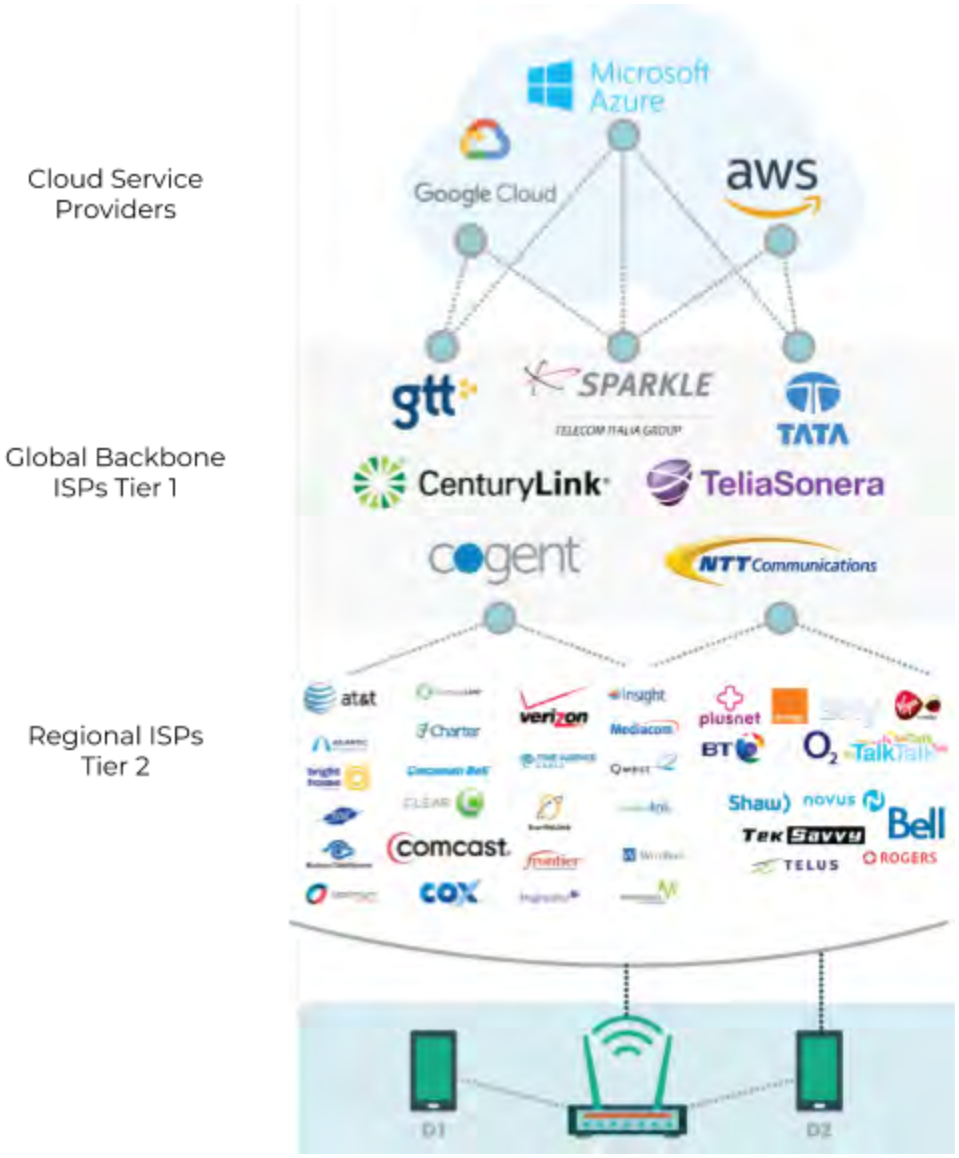


***Fig. 2**: The path between two phones where one is on Wi-Fi and the other is on cellular*

Companies that operate networks, and the service providers that use them, are motivated to continue with the status quo. Facebook and Google depend on centralizing data collection. AT&T, Sprint, Verizon, Rogers, Bell, and others depend on people willing to spend more money consuming data from (and providing data to) centralized services. These businesses grew up out of the model where people would pay monthly to consume television and media content: the Internet is just a newer version of the same thing. There is very little motivation for these companies to embrace any technology which will shift this balance, and this is

why we as a society continue to spend considerable effort to expand infrastructure. Cells are getting smaller, more fibre is being laid, and more storage capacity is being brought online.

Infrastructure is good, and having reliable dependable and fast connectivity is extremely useful; however, there are limits. There is only so much bandwidth available. Wireless channels are getting wider. ISPs are asking for more licensed spectrum. Unlicensed spectrum is being saturated with networks as people's home routers use all of the non-overlapping channels at once with technology like multiple input and multiple output (MIMO) antennas. As ISPs reserve more and more spectrum, there are areas where the spectrum is not used efficiently at all and sits idle (for instance, in the countryside). Research efforts, which opportunistically use licensed spectrum, typically don't gain traction because the ISPs have no motivation to change the status quo. Most ISPs would rather let the spectrum sit unused than let someone else make use of it -- especially if people aren't forced into their rigid service agreements and payment structures.

Internet-less Data Transmission

Going back to the examples of messaging, an easy solution is to avoid using the Internet for messaging. This can be done today in apps. We have done this within our own YO! application, which can setup a hotspot and allow anyone within range to share files, messages, and content without using the Internet. It can also operate in such a way that if two devices are on the same Wi-Fi network, the messaging will occur using only the local Wi-Fi network (not the Internet). The biggest drawback with this technology is the limited range of a single hotspot or Wi-Fi network. The biggest benefit is all three of the layers above the hotspot are eliminated. There are two ways in which Internet-less data transmission can be deployed over a wide area. First, one can deploy new infrastructure that is not connected to the Internet, or only uses the Internet when trying to communicate to devices outside of this newly deployed infrastructure. This is essentially starting a new Tier 2 ISP. Some cities, communities, and companies are trying this approach currently. This requires heavy investment in infrastructure.

The second method, is to attempt to enable multi-hop connectivity with the end-devices themselves (phones, IoT devices, computers, etc.). With this second approach, the biggest drawback is not having enough density for the devices to form a mesh. This can be addressed by introducing caching and delay tolerance into the protocols. The other blocker thus far has been the actual difficulty in achieving multi-hop, ad hoc connectivity with the devices without rooting the device, applying kernel patches, and using only software.

With several years of development and a team of PhDs, Scientists, Engineers, and advisors who specialize in mesh networks, have built companies around mesh networks, and have experience in the telecom industry, RightMesh has been able to create a library for mobile devices which provides the ability to avoid the upper layers in Fig. 1 and Fig. 2 and communicate over an arbitrary number of hops without using the Internet. In the case where density is not high enough—for instance, two neighbourhood meshes which form—RightMesh continues to use Tier 1 and Tier 2 networks (and optionally can use cloud providers) in order to link geographically separate meshes. Essentially, this has created a new class of network (a Tier 3 network) whereby individuals can act as their own local ISP.

P2P vs Infrastructure-less

There are other messaging apps or networks which are considered peer-to-peer apps; for example, Telegram claims to be p2p as do Ethereum Whisper, and many others. This means the centralized aspect of AWS, Google Cloud, or Azure may be eliminated. Connectivity is done in a peer-to-peer manner, but only if all of the devices have a direct Internet connection already. This means the devices still have access to a wired network, Wi-Fi using an ISP, a cellular plan, etc.

In the two devices in one room example, if the app is clever, it will detect that both devices are on the same local area network (LAN), and use the local IP address to connect to each other and exchange data. If it is not clever, it may perform a discovery process where the external IP address is used in the discover process and have to traverse the network address translation (NAT) in the router at the edge of the network. In the case where one device is on the Wi-Fi network and the other is on the cellular network, the external IP address of the Wi-Fi network would be used along with the IP address of the cellular phone. There is usually some added complication to getting around the firewall the cellular companies use to prevent servers running on phones from being reachable, but hole-punching is a well established technique to get around this (ie: running an Internet reachable server or connecting through peers which do not have firewalls or NATs to help negotiate open ports between two peers behind incoming firewalls, or NATs) - this is how skype, video games, and many apps function and make connections between two peers directly instead of operating with a relay server in the middle handling the traffic.

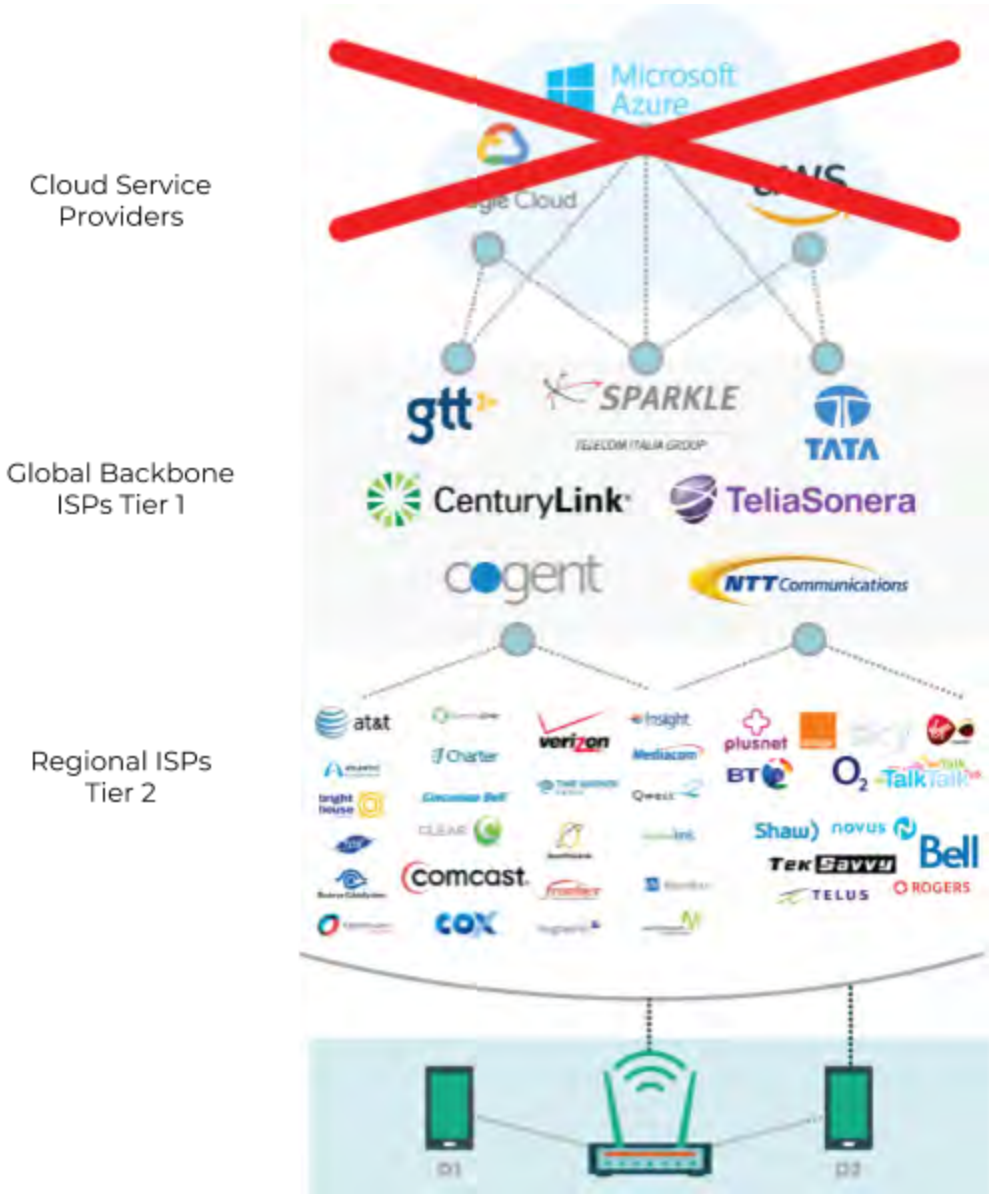


***Fig. 3**: p2p typically only removes the top layer (cloud service providers) while infrastructure-less removes all three layers in some cases.*

Wireless Mesh Networks (WMN) Vs Tradition Wireless Local Area Networks (WLAN), Wireless Personal Area Networks (WPANs), Cellu lar Networks, Infrastructure Networks

A Wi-Fi wireless local area network (WLAN) has a central hub called an access point (AP) which is used to provide infrastructure to the station devices (STA). STA devices could be devices with are stationary or

mobile such as mobile phones, computers, IoT devices, TVs, or anything that can connect via 802.11 Wi-Fi. The main function of an 802.11 network is to remove the requirement to plug devices directly into the router. Devices are free to come and leave and we no longer think about what happens when we return home with our devices: they just "have Internet" when they are in range.

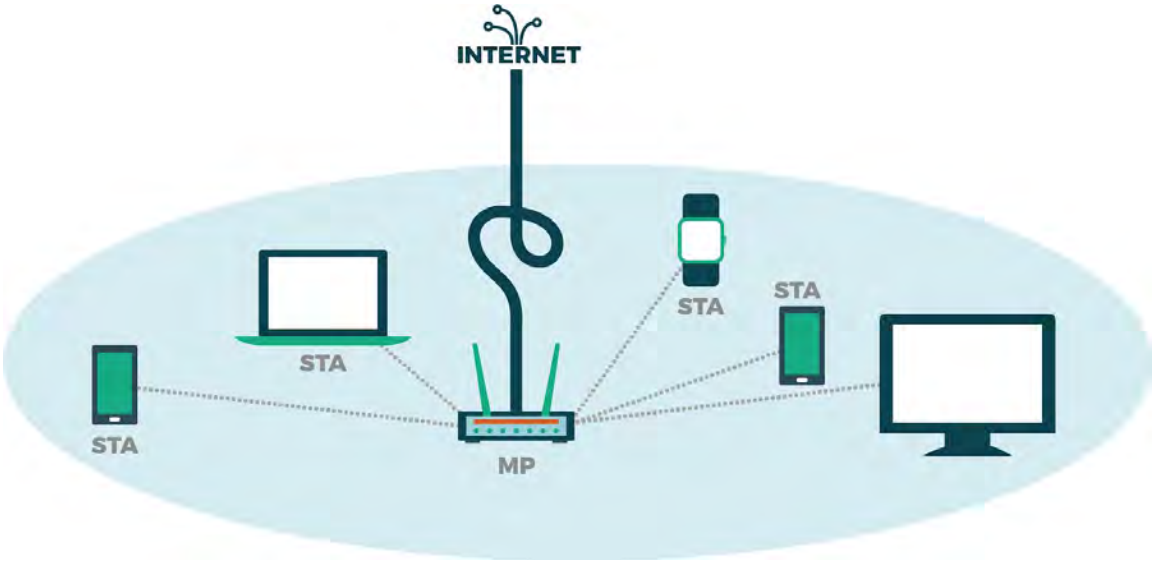


Fig. 4: *802.11 Wi-Fi WLAN with fixed hardware AP, some fixed and some mobile STA.*

In a home router, the AP is fixed and does not move (Fig. 4). Many mobile phones can also provide AP functionality by setting up a hotspot. This can be used to provide a local network only, or to share Internet access. Typically, people assume that hotspots always provide Internet access, but this is not necessary. APs on phones may be used as infrastructure by which one can provide "mobile infrastructure" to other STA devices. In Fig. 5, a similar network can be provided; however, the wired network connection between the router and the Internet has been replaced with a cellular Internet connection. In both Fig. 4 and Fig. 5, the Internet connection is completely optional. The network will still function without it in some ways. For instance, the laptop could still stream a pre-downloaded video to the television through the AP without the Internet. The biggest difference between Fig. 4 and Fig. 5 is that if the AP phone leaves, the network will cease to function. In Fig. 4 this is also true, but it is not so easy to disconnect a stationary router compared to just walking away with the AP mobile phone.

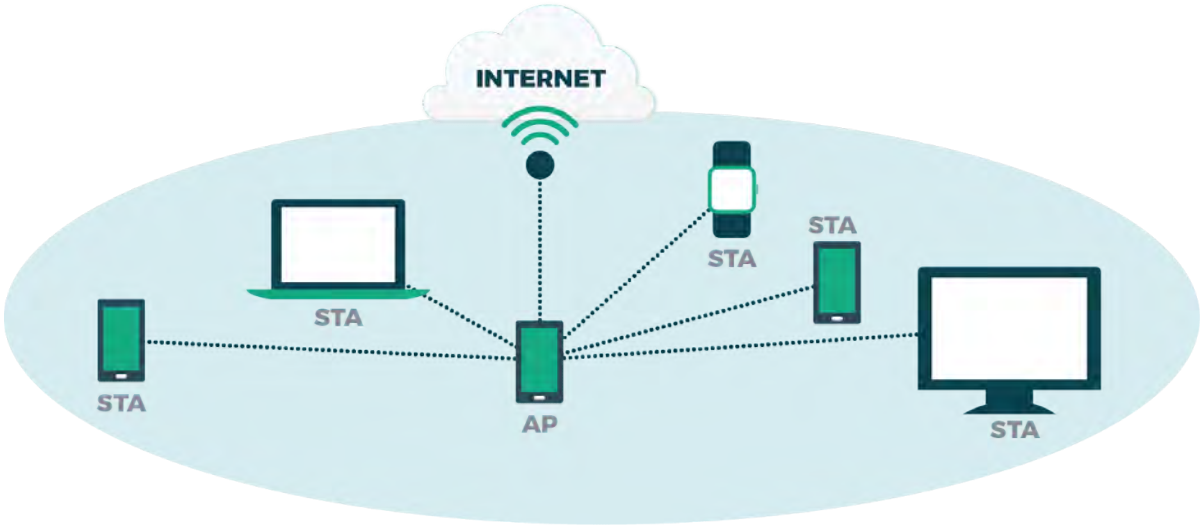


Fig. 5: *802.11 Wi-Fi WLAN with fixed hardware AP, some fixed and some mobile STA.*

A wireless mesh network is different from a traditional wireless network network like a Wi-Fi WLAN or a Bluetooth Personal Area Network (PAN). Instead of offering a central hub that offers a circular bubble of coverage, an 802.11s wireless mesh network provides a cloud of coverage that can span a much larger area. It does this by linking together many hotspot-like routers to form one continuous network (Fig. 6).

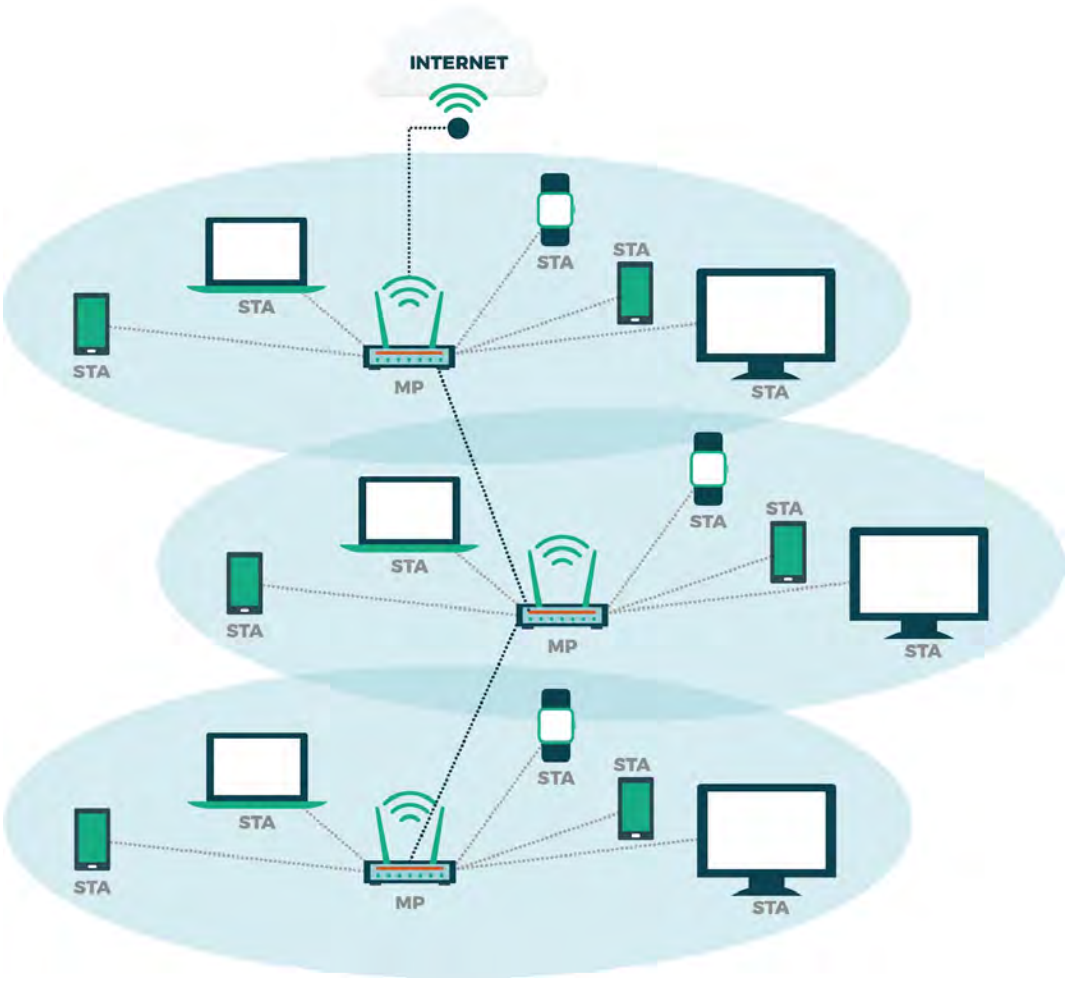


Fig. 6: *802.11s network with three MPs and one Internet connection*

Typically, wireless mesh networks are deployed using hardware, often on street poles or small towers similar to cellular deployments. The difference between a cellular network and a wireless mesh network is usually that a cellular network has fibre connecting each tower to infrastructure. In some cases, a cellular network can be similar to a mesh network if the towers are connected together with a wireless backhaul. This is often done in more rural / less dense areas since the wireless backhaul may not be able to carry as much traffic as a fibre line and is affected by things like weather more easily. However, it is much more affordable. When a wireless backhaul is used, the backhaul is often on a different frequency than the one which the wireless handsets connect to the towers with. In Fig. 7, the cell towers with yellow lines are connected via fibre, while the topmost cellular tower uses a wireless backhaul.

Fig. 7: *Cellular network with a mixture of wired and wireless backhaul* (http://odec.ca/projects/2007/hopp7m2/cellular_phones.html)

A wireless mesh network often has only a small subset of devices which directly provide Internet into the network. The mesh network devices must then maintain routes / paths towards the Internet. Further a wireless mesh network is different from a cellular network because wireless mesh networks often operate in free spectrum, whereas cellular networks operate on licensed spectrum. Cellular networks also have additional hardware infrastructure to handle billing, handover and other features depending on whether it is a 2G, 3G, 4G, or other network. In Fig. 6, this would be contained in the outdoor transmission equipment and radio relay stations. In a mesh network, this logic is typically contained within the mesh hardware itself. Mesh networks are typically designed to be deployed with less planning than a cellular network. They are designed to configure themselves automatically while reacting to environmental conditions and congestion. There are typically more paths available, whereas a cellular network may be designed to minimize infrastructure cost (i.e., focus on few expensive backhauls).

"Software Only" Mobile Mesh vs Infrastructure Mesh, Hardware Mesh

A mobile wireless mesh network (mWMN) is a variation of the wireless mesh network where the routers are mobile devices (phones) themselves. This is quite different from the hardware mesh networks for several key reasons. First, the mobile devices are not in a fixed location. This means network partitioning may occur (where the network splits) making some portion of nodes unreachable to others for some period of time.

The mobile devices, which are typically phones, do not often support advanced features that are required to support meshes in the same way that hardware can. On a hardware router, the manufacturer controls the chipset and operating system on the device and can apply kernel patches and access the routing table. This means protocols like 802.11s (a mesh networking standard for Wi-Fi devices) can be supported by patching the OS kernel as long as the Wi-Fi chipset supports it. 802.11s allows devices which are located many hops away from each other to appear as if they are located nearby. From a link-layer perspective, they all appear to the layers above as if they are on the same WLAN (hotspot). Essentially, it converts all devices which would normally be separate Access Points (APs)/ (hotspots) into Mesh Points (MPs) as in Fig. 6.

In Fig. 4 and Fig. 5, internet protocol (IP) addresses are provided to all of the devices because the device acting as an AP also provides a dynamic host configuration protocol (DHCP) server typically. The job of this server software is to map the media access control (MAC) address to an IP address. A MAC address is the physical address of the Wi-Fi chip in the phone, laptop, or other device and take the form '00:00:00:00:00:0X'. These are meant to be unique across all devices; however, these can be faked sometimes by software and there are no guarantees they will actually be unique since it depends on cooperation from the manufacturers of Wi-Fi devices. An IP address is used by the routing protocols to determine how to get packets from one device to another.

Fig. 8: *Two APs with different sets of IP addresses*

For instance in Fig 8, the phone with IP 192.168.1.4 on the left, may wish to send a data to the the TV on the right with IP 192.168.1.25. During the DHCP discovery process (when the devices obtain their IP address from 192.168.1.1, they set their default route to 192.168.1.1. When they encounter an IP address they don't have stored locally yet, they will send a request to their default route to determine where to find this device. 192.168.1.1 will tell 192.168.1.4 that it it can reach 192.168.1.25 through 192.168.1.1. It is also possible to reach

192.168.5.4 in a similar way; however, when the data arrives at the router, something special called Network Address (NAT) is required to determine which device the incoming traffic from the Internet is intended for. If we were able to link the TV at 192.168.1.25 locally with 192.168.5.4, there would need to be a similar translation done to convert the IP addresses from the left network to the IP addresses in the right network. There are protocols which can achieve this type of translation; for example, the border gateway protocol (BGP) can perform such translations..

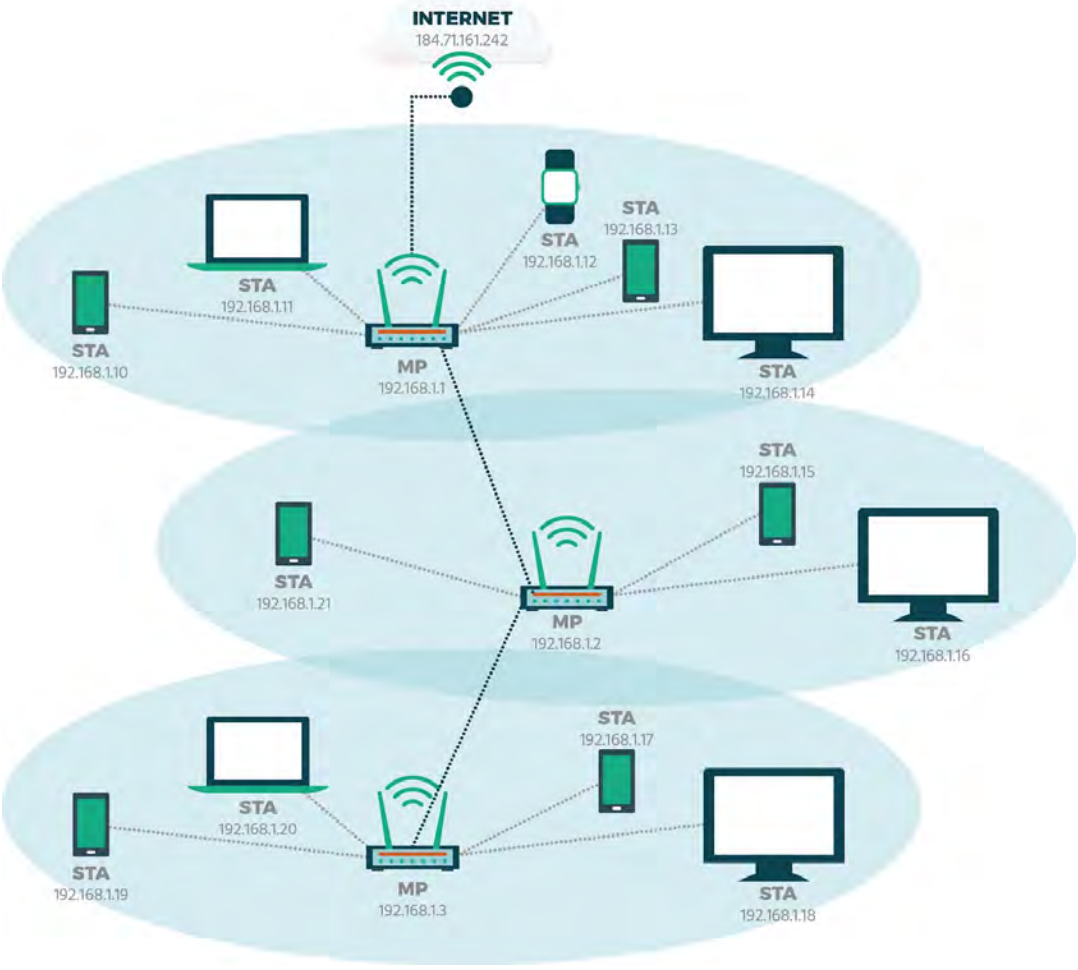


Fig. 9: *IP Addressing in a 802.11s mesh (all devices in same subnet range)*

The alternative is an 802.11s mesh, or something similar using Zigbee or Bluetooth 4.x or higher. In these types of meshes, the mesh forms at the link layer, meaning that all of the devices appear as if they are all on one hotspot, or all on one wired network. This means all of the devices can obtain IP addresses in a consistent manner and routing tables can be built by the operating system quite easily (Fig. 9).

IP Addressing Limitations on Mobile Phones

On an Android phone, 802.11s cannot be used without rooting the device. So without being able to use 802.11s, the only means to form a mesh on the mobile phone are through technologies which were really only meant to connect devices in a hotspot model (one hop away from a central device), and technology must be developed to link these hotspots together. Even if the hotspots are linked together, an IP address only makes sense within the local hotspot, and not any further beyond. As a result, it would require something like BGP to be implemented (since it would again require rooting the phone to make modifications to the routing table).

Since it takes a rooted device to manipulate the routing table directly, it is not possible to tell the routing table how to reach devices in other hotspots easily. Similarly, a MAC address from a BT connection is meaningless when trying to route packets using TCP/IP (for an end-to-end connection across the mesh). Further, even if it were possible to do such a thing, normal TCP does not allow for multiple paths unless the mTCP protocol is used, again which requires a rooted device to use.

End-end data transmission limitations

One of the biggest challenges with building a mesh using existing TCP on the phones is that of end-to-end communication and path reliability. As these unreliable links grow in number of hops, the likelihood of a successful delivery becomes more and more remote. Consider a path that is ten hops long, where each path has a 99% chance of success on each hop. The probability a packet will reach the destination is 90.4%. If the success rate of each individual hop drops to 90%, the overall probability drops to 34.9%. In order to improve the overall success rate, end-to-end protocols must also work with one-hop protocols to increase the success rate of the individual hops. A complete end-to-end re-transmission must be avoided wherever possible.

Core RightMesh Technology Overview

The core of RightMesh is comprised of:

1. A local mesh, which aims to build a platform-independent, locally-connected, multi-hop, ad hoc network between the phones;

2. A globally-connected network of these local meshes
3. A micropayment channel system that allows for mesh users to sell their Internet data into the mesh, and other mesh users to purchase this data. Devices along the path on the mesh are rewarded. Devices which provide reliable, consistent Internet connections, an Ethereum node, and RightMesh tokens are also rewarded for facilitating Internet transmission between meshes.
4. An API / SDK / Library which allows developers to build RightMesh apps
5. Reference applications for Android, Java, and the cloud to support a growing ecosystem.

The RightMesh networking stack shown in Fig. 10, builds off of the success of existing Internet protocols. The design is a layered design, so improvements can be made iteratively on each of the layers without having to do a full redesign of the entire system.

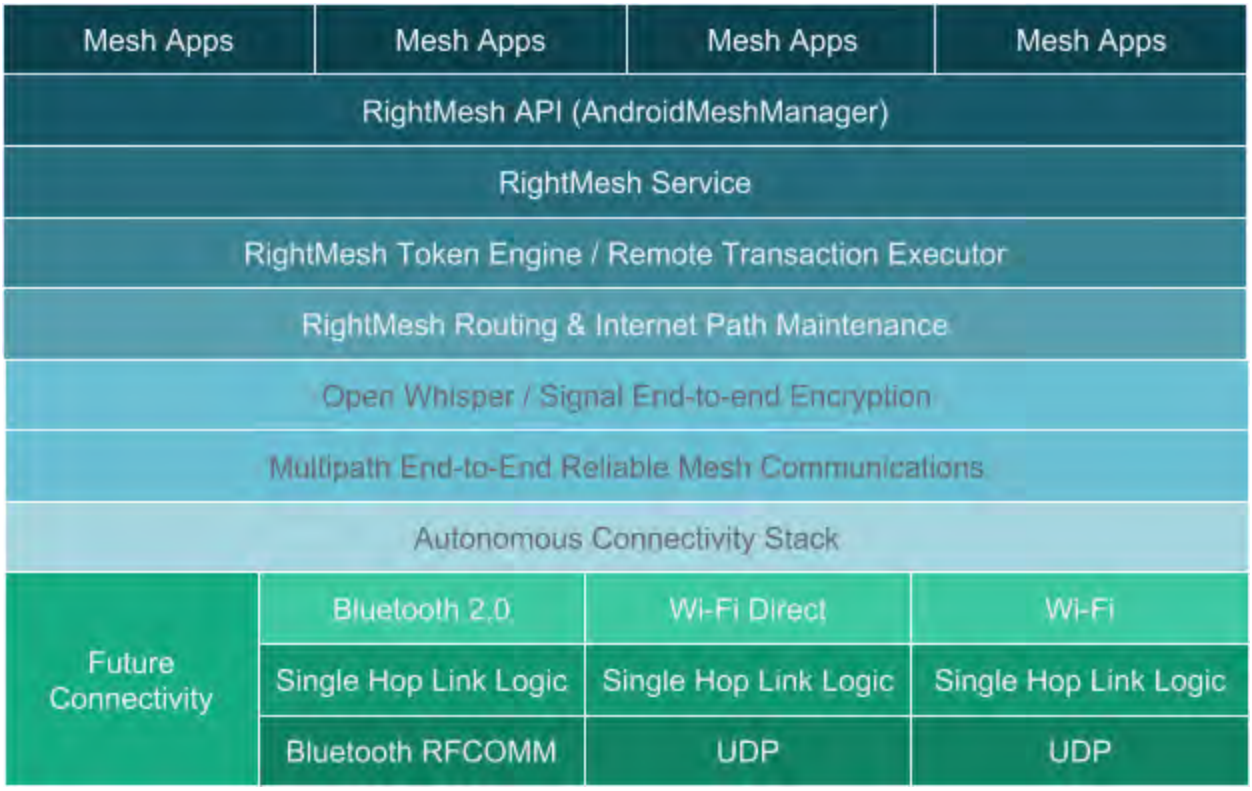


Fig. 10: *Layered RightMesh Protocol Stack*

Local Mesh Connectivity

The RightMesh protocol in conjunction with the RightMesh Android library handles autonomously forming connections via Bluetooth, Wi-Fi, and Wi-Fi Direct between devices via a peer discovery / topology creation

protocol. RightMesh devices are assigned a locally-generated unique identifier in the mesh based on an Ethereum public address which we call a MeshID. This MeshID maps local and changing IPv4, IPv6 and MAC addresses to a single, consistent global device identity. The mesh protocols and systems form an autonomous self-configuring, self-healing, self-optimizing, self-protecting (self-*) system. The locally connected multi-hop ad hoc network is comprised of a hierarchical layered architecture. This architecture starts at the lowest layers by abstracting existing network stack one-hop links as if they are link layers in a traditional network stack. For instance, a Wi-Fi link between a Wi-Fi hotspot and a Wi-Fi client is treated more closely to how 802.11 treats a MAC layer link rather than as a link that already has an IP address and could support TCP connections on. On top of this, an end-to-end transmission control protocol is implemented which takes into account our unique (and patent pending) switching techniques to link hotspots together, as well as this hierarchical routing table. This transmission protocol ensures reliable delivery between devices on the mesh since the lower layers use UDP. It also has the ability to send data across multiple paths at once and recombine at the receiver side. This was influenced by multipath TCP (mTCP). The protocol also has some limited ability to perform some delay tolerance because it has some loose coupling with the the lower layer, allowing for limited retransmissions at each single-hop along a multi-hop path to avoid end-to-end timeout and retransmission. This was motivated partially by protocols like Licklider Transmission Protocol (LTP).

Bluetooth 2.0 RFCOMM was used as a starting point because it was possible to make a connection with other peers without requiring pairing. With our Wi-Fi Direct and Wi-Fi implementations, the same is also possible. RightMesh makes connections programmatically using three different types of next-hop links. Within our design, RightMesh can add support for higher versions of Bluetooth as we figure out ways to make the connectivity occur without user intervention. We may be able to do this by making use of some of the other connectivity pathways we already have as a way to signal information between devices to set up the faster connections.

The autonomous connectivity layer does the job of assigning internal roles to devices in our network. This decides whether a device will be in hotspot mode or not, which devices to connect via Bluetooth, whether to use Wi-Fi, Wi-Fi Direct, both, or all three. The RightMesh approach to autonomous connectivity is something that will constantly get better, but it was kept simple as a sort of MVP state. In fully-automated mode, the user will only need to select whether they wish to participate as a forwarding node, and whether they wish to share their Internet, or not. If they wish to sell their Internet, they will also need to set the price

they wish to sell it for (in Mesh Tokens). Conversely, if the user wishes to consume Internet, they must set the price they are willing to purchase Internet for (in Mesh tokens). If they do not wish to pay any mesh tokens and there are no free paths, the apps will still function, but they will only be able to use a localized version of the mesh. It is also possible, in advanced mode, for users to control exactly which internal role the device should use. This capability is packaged automatically with every app that uses the RightMesh library via the RightMesh Service.

We make use of a clustered routing where hierarchy is imposed on the devices based on the internal roles the devices are assigned. This means that not every device needs to know the connectivity to every other device, allowing the RightMesh network to scale significantly higher than competing approaches. This same cluster-based architecture lends itself well to enabling caching in the network which is also on our roadmap. For instance, the same nodes that are cluster heads would be ideal candidates to also be a cache of common apps, ads, and multimedia content.

Combined with the routing layer and the one-hop connectivity layer, multipath end-to-end reliable communication forms a really unique and valuable part of the RightMesh solution. This is what distinguishes RightMesh from most of its competition. There are a few ways communication typically occurs in mobile meshes:

1) Broadcast to everyone (either using UDP + existing broadcast / multicast approaches, or TCP on a link by link basis - no end-to-end capability)
2) Single-path end-to-end TCP (with many limitations as outlined below)
3) Best-effort UDP communications with no reliability

Many existing mesh approaches simply make use of existing TCP to provide end-to-end connectivity. However, TCP is not well suited to a mobile mesh network for several reasons:

1. Unless rooted, mobile phones do not let the user customize the version of TCP being used.
2. Mobile mesh networks are made of devices that frequently connect and disconnect. When this occurs, a TCP connection would require end-to-end reestablishment of a connection, with something like a 3-way handshake.
3. With IPv4 It is often impossible to make an end-to-end TCP connection because the IP address in one hotspot means nothing to the neighbours three hotspots away. As such, there is no mechanism to exchange this information between hotspots and have the routing automatically work. In this

case, it may be possible to have TCP on each single-hop link, but there are still the same drawbacks from some of the other bullet points to be aware of. In the case of performing TCP on each link, there is still no mechanism to prevent an entire end-to-end path from being saturated with traffic (the congestion control will only work on a link-by-link basis, leaving the queues at the intermediary nodes to potentially overload).

4. TCP often gets interference and congestion mixed up. It may start a backoff unnecessarily thinking that congestion is occurring when it is experiencing temporarily poor network conditions due to external factors (e.g., a vehicle driving through the path of the signal, a microwave being turned on, a tree being between two people who are moving, etc.).
5. The TCP on most non-rooted phones cannot handle multiple paths. This means even if your device has a Bluetooth, Wi-Fi, and Wi-Fi Direct connection available, it is only able to use a single one of them for one data stream. This also applies to Internet connections out of the mesh as well. There are existing versions of TCP that can do this, notably mTCP; however, it is almost never included in commercial phones.

RightMesh borrows concepts from delay-tolerant network protocols such as LTP and has combined them with multipath-TCP to create a delay-tolerant protocol when the network becomes fragmented, but high performance in the cases where it is well connected. RightMesh also uses concepts from Software Defined Networks, Overlay networks and self-* networks.

Rightmesh supports end-to-end encryption. More details are provided in the encryption section later in the document.

Global Connectivity - Linking Meshes Together

While one day it may be possible to link the entire world with one “local” mesh without using any of the existing infrastructure, this is not practical today. To make RightMesh more practical sooner, and to enable apps that work like everyone expects, it is necessary to be able to link separate RightMesh meshes together. Consider a mesh in Vancouver, Canada and a mesh in Dhaka, Bangladesh. If there is at least one device in each mesh which are willing to share their Internet data into the mesh, then these two geographically separate meshes together can form one large mesh. The distance between the meshes doesn’t need to be that extreme: it could be one neighbourhood connecting to another neighbourhood in the same town.

There are few problems when trying to do this type of linking. First, is that cellular companies and ISPs often block incoming server ports on mobile devices, making it difficult to make a connection directly from one phone to another on the Internet. Second, if there are multiple devices behind one router (like at an office, or home), network address translation (NAT) is required to map outgoing connections back to the device which made the request. For instance, if your phone and computer both visit the Google website at port 443, and the phone searches the term "hello", and the computer searched "mesh", NAT would know to route the first request to the phone, and the second request to the computer (this is a massive simplification, but this is the general idea). In order to get around these problems, RightMesh must provide a layer which allows devices which aren't behind NATs and Firewalls to facilitate connectivity between devices that are. This layer is called the Superpeer layer, and takes motivation from other p2p protocols, video conferencing, and other well known apps which use UDP hole-punching.

Currently, global connectivity is limited to connecting multiple separate geographic meshes together, and does not support "general purpose Internet connectivity". This means, RightMesh devices can't yet natively route Facebook Messenger into the mesh unless Facebook integrates RightMesh into their app. Similarly, the phone user will not be able to open their web browser and visit the Google homepage. They will be able to use a RightMesh app in Vancouver, and talk to someone in Bangladesh on the same app as if they were on one large mesh network. General purpose Internet requires us implementing a proxy on the phone side which translates Internet traffic into RightMesh traffic towards Superpeer devices. At the Superpeer devices, a NAT would be implemented which would also translate the RightMesh traffic back into IP traffic.

Micropayment Channels for Incentivization

With the local mesh connectivity and the global connectivity through the Superpeer layer, it is now possible to link meshes together technically. However, without incentivization the only people who will share their Internet into the network are those who have low-cost data and a kind-hearted nature. This model works for some networks like Tor, which operates on a voluntary basis and depends heavily on institutional participants who encourage free speech, such as universities. The problem with a mesh adopting this model is that the mesh requires local participants to be willing to share their data into the network. This most often means individuals. In order to motivate these individuals, we believe they should be able to earn something for providing their data, their battery life, their storage, their sensor information, and their processing power.

To enable incentivization, RightMesh has developed a micropayment channel solution based on microRaiden and implemented at the Superpeer layer. This allows devices to sell their data into the network at their own set price, while allowing other devices to purchase this data at a market rate (the protocol will select the lowest cost route available). Devices in between the buyers and sellers are incentivized for participating, and those operating the Superpeer layer also have the opportunity to earn tokens for staking their tokens and facilitating the communication (note: these devices provide UDP hole-punching and payment hub functionality as well).

The RightMesh API / SDK / Library

The RightMesh API provides developers with an event driven framework enabling simple discovery / updating / removal of other peers in the mesh running the same app, sending and receiving data, and end-to-end encryption without the developer being skilled in any of these areas. On top of this discovery protocol, the API packaged with the protocol handles splitting up datastreams into packets, which are routed across the multi-hop mesh network using the parts of the protocol responsible for reliable end-to-end communications and delay tolerance. When a full datastream arrives at the destination, an event fires at the receiving peer notifying the developer some new data has arrived.

One of the philosophies behind RightMesh is that a user should never have to be involved to pair a phone, join a Wi-Fi network, setup a hotspot, or otherwise be involved. It should operate similar to how a cellular network manages handover between cellular towers without the users of the phones knowing that it is even occurring. However, if the user wishes to use advanced functionality and control this to some extent, this should still be possible. He or she should be able to disable Wi-Fi or Bluetooth and the mesh should use whatever is still available to continue operation as best as it can with what is provided by the user.

A second philosophy of RightMesh is that the user should always be in control, not the developers. That is to say, developers using RightMesh should not be able to control whether the app only participates as Wi-Fi client, it turns on hotspot mode, or Bluetooth. If this were possible, one could imagine a developer creating an app which only participates in RightMesh as a “leech” on the network, never providing any service to others. If a user wishes to operate in this mode, this is perfectly acceptable as they will have fewer opportunities to earn rewards operating as periphery / leaf nodes in the network. In order to earn tokens by relaying traffic, one must operate as infrastructure and provide service or virtual infrastructure to others.

Developers of a RightMesh app get the benefit of having the power of RightMesh built into their apps natively. RightMesh will send data through the local mesh when possible and fall back to the Internet when not possible, greatly increasing the efficiency of communications (most apps today are designed to communicate directly with the Internet even if the person you are sending data towards is in the same room as you). The increased efficiency may result in lower energy usage in the network as a whole. For instance, offloading connectivity from a 4G network to Wi-Fi or Bluetooth connectivity for some portion of the devices could lower energy consumption. It may also result in increased efficiency in terms of bandwidth costs for app providers. Consider an app like Facebook Messenger or Slack where messages move from the phone to a cloud service, back down to a second phone in close proximity. There would be Internet costs for these services providers for the data to move to centralized servers and back to the phones. With RightMesh, this transmission could occur locally between the two phones. If the phones are farther apart, it would fall back to a similar model of sending to and from the Internet. However, if there are large groups of phones for the data to be sent to, RightMesh could help again. In this case, even across the Internet, if some of the phones exist on a local mesh together, RightMesh would send across the Internet once for the entire local mesh, where it would then be distributed to all of the receivers using the mesh protocols. The cost savings here would scale with the number of receivers in the same mesh.

Users of RightMesh apps will also benefit from the same types of cost savings. The limited bandwidth on the existing infrastructure will be used to obtain new content for a mesh, and existing content can be distributed locally within the mesh. Existing telcos are motivated to have everyone pay to consume the same data over and over again. While people should pay something to consume content (to reward the creators, and the parties that facilitated the transmission), RightMesh believes this cost should be significantly lower once the data has been distributed into the mesh compared to the initial transmission (since the first hop from the Internet is where bandwidth is limited by the availability of low cost infrastructure).

Developers will also get the benefit of all of the other RightMesh enabled apps. Density is often a concern in mesh networks; however, as a developer it is not required to have high density via a single application. For example, an emergency app could forward data through a device only running a messaging app (if the app was built with RightMesh), and that could forward through a device running a game until it eventually reaches the other device running the emergency app on the other end.

RightMesh apps are not required to be deployed only on Android devices. It is possible for RightMesh to run on any device that supports Java runtime. This could be computers, raspberry Pi's, remote weather stations, sensors, and other devices. On these devices, there is less autonomous connectivity built-in; however, they are well-suited to act in a more infrastructure role, providing hotspots for other autonomous mobile phone devices to automatically make connections with them. It is also possible to run a Java RightMesh app on a cloud service if one wishes to develop an app that interacts with traditional centralized architectures like web servers, relational databases, etc. An example of this type of app might be a server app which collects sensor data from a variety of sensors scattered throughout the RightMesh ecosystem and stores it in a centralized relational database. There would be a corresponding RightMesh sensor app that would run on the sensor devices and send its updates to a set of sensor sink apps running on the cloud. RightMesh protocols would figure out how to get the sensor data there. Corresponding websites could then query the relational database in the normal fashion and display the sensor data live as it is being returned from the mesh.

RightMesh Reference Apps, Ecosystem

In order to kickstart the development of RightMesh apps and an ecosystem around RightMesh, we have begun providing open source reference implementations of various types of apps.

The first and simplest apps are of the "Hello World" variety, including the "Hello Mesh" app. Related to this we have released a Java version of the same app called "Hello Java Mesh" which can be run on a computer and interoperate with phones on the same mesh. Phones and computers can send a "Hello Mesh" message to each other, and the developer can see how similar the code is on either side, even though the Android, Linux, and Windows platforms are quite different.

During some of our testing, we developed a "ping-like" app called "Reflect" which can be used to send a ping message from one phone to another, and replay the message back to the sender. This can be used to test connectivity on the mesh.

We also created an app called "Ripple", which was used to demonstrate visually how the routing protocols on RightMesh work. In this app, it is possible to send a "color" to another phone in the mesh. All of the devices along the path will change to the sent "color" as the packets move across the mesh. This

demonstrates that RightMesh does not use broadcast routing, and in fact, computes a unicast route between two peers.

Most recently, we released a messaging app called "MeshIM", which supports peer discovery, basic user profiles, and messaging between peers using RightMesh.

To support the general blockchain and Ethereum communities, we have begun an open source port of the microRaiden project from python into Java (the language that RightMesh is currently written in).

Finally, in order to enable developers to create their own Superpeer implementations and control channel creation and management strategy, we have provided a reference implementation of the RightMesh Superpeer.

3. The Local RightMesh Network

The aim in this section is to explain the details about the local network connectivity protocol in greater detail, covering internals to the library such as:

1. MeshID which replaces IP addresses, MAC address, and other addressing schemes
2. MeshPorts, which are used to multiplex traffic from the RightMesh service to any number of apps running at the same time
3. Internal roles which dictate how a device performs requests and responses within the protocol
4. Peer discovery, one-hop transmission, and control packets
5. Autonomous formation
6. Data transmission
7. Routing
8. Encryption,
9. Local multicasting and broadcasting.

In all of these cases, the local aspects of the mesh formation and data communication are emphasized. The next section goes into detail about Internet communication.

MeshID

Given that RightMesh is able to support connecting together multiple Wi-Fi hotspots—each with their own set of IP addresses (both IPv4 and IPv6), as well as connecting via Bluetooth (with MAC addresses), and in the future other networks where there may be even more different addressing schemes—one the first problems we aimed to solve is how to identify devices in the network uniquely. While building YO! (one of the company's first offline apps), this was handled in the typical manner where unique IDs are generated from an Internet-connected server. In a mesh where the devices may never touch the Internet, or may not for a long period of time,or the Internet is censored, this makes it impossible to form the identity. It is a chicken and egg problem. With RightMesh, we needed to generate the ID on the device without requiring the Internet to do so. Researching this problem led the company into cryptocurrencies, where this problem had already been addressed and proven to do so in a way where there is almost no chance of ever generating the same ID twice.

Currently, RightMesh generates an Ethereum account using the Ethereum-j library. The account generated is compatible with any popular Ethereum client, such as geth, mist, or myetherwallet. This identity is generated once when the RightMesh library first launches on the device, and remains on the device until the user has removed it manually. This means if RightMesh apps are installed and uninstalled, the same identity will be present unless the user removes it. All RightMesh apps that are running at the same time also share the same identity, similar to how your computer has the same IP address for your web browser, your Slack client, and your games (unless you leave your house and travel to work with your computer and get a different IP address at your new location). With RightMesh, despite all the movement and changing IPs while you move, your RightMesh identity will stay constant. This permanence is how other devices in the mesh will always be able to deliver data to the right device.

The identity on the mesh is the public Ethereum address that gets generated along with the account. The generated account is encrypted using a default password that RightMesh provides (as a proof that the service can do the encryption correctly). It also contains the public and private key associated with the account to ensure it works on the Ethereum network when executing transactions. At launch time, RightMesh aims to have the MeshID functioning such that a user will be able to set their own password for the encryption so that their account is locked and protected by the password as they would expect with an account generated by any other client.

Mesh Ports, Service Architecture, Multiplexing to Multiple Apps

On Android, the RightMesh library functions as a service. Multiple apps can make use of the service at the same time, provided they are all listening on different mesh ports. The RightMesh Developer's Portal (shown in Fig. 11) allows developers to register keys which are associated with each mesh app they build. When registering the developer key, they also pick which mesh port(s) the app will be listening on and verify that no other apps are using the same key. The developer who created the key may share access with other developers, so teams can collaborate on the same app without sharing login information. If one of the developers leaves the project, their access to generate valid keys may be removed. Farther down the technical roadmap, the developer portal will also be used to help developers debug mesh connectivity through visualisation, file bug reports, deploy updates through the mesh, and as a mesh analytics platform.

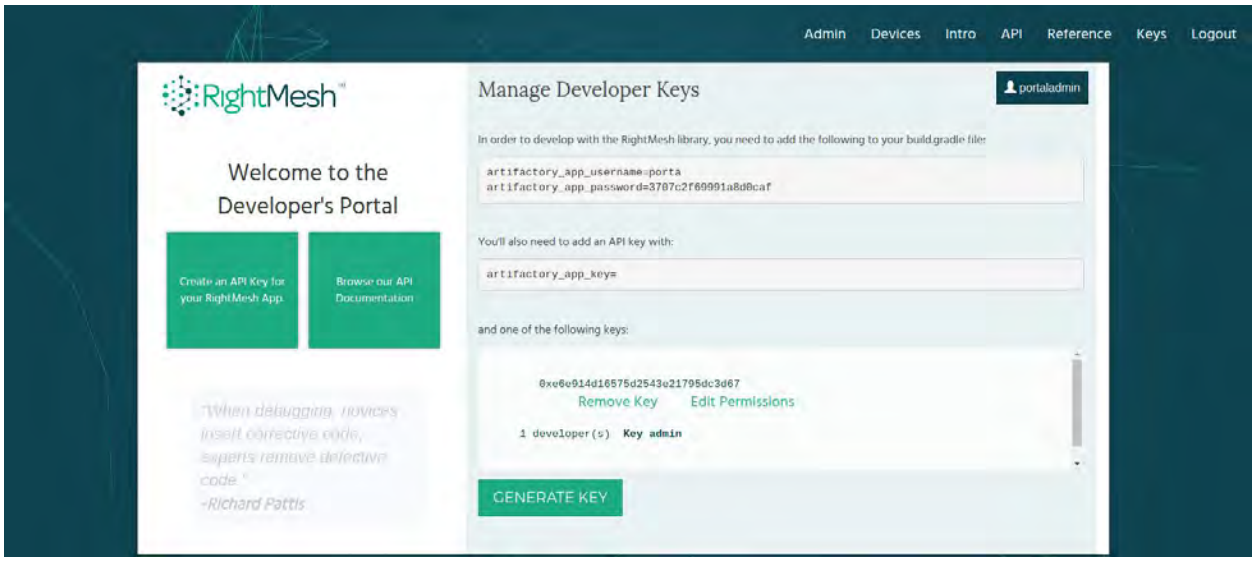


Fig. 11: *RightMesh Developer's Portal*

When the app connects to the MeshService, the service parses a cryptographically-signed license key that is generated at compile time and packaged with the app by our RightMesh Gradle plugin. (An example Gradle file for compiling with RightMesh can be found on our "HelloMesh" project on GitHub. The signed license key file requires a valid developer account with access to the key at compile time. Inside this license is the developer key, and mesh ports that the app is allowed to use. Again, similar to the MeshID problem, we tried to design this system so that apps may form meshes without requiring Internet access to validate the library (although we make the assumption that Internet access is available at compile time for the developers).

Fig. 12 shows the RightMesh Service running on a single phone, with three different apps running at the same time. They are all running on different mesh ports. Each app also comes with a portion of our library we call the AndroidMeshManager, which performs all of the logic to connect to the service, and to fire events such as Peers joining or leaving the network, data arriving, or the result of encryption keys being exchanged.

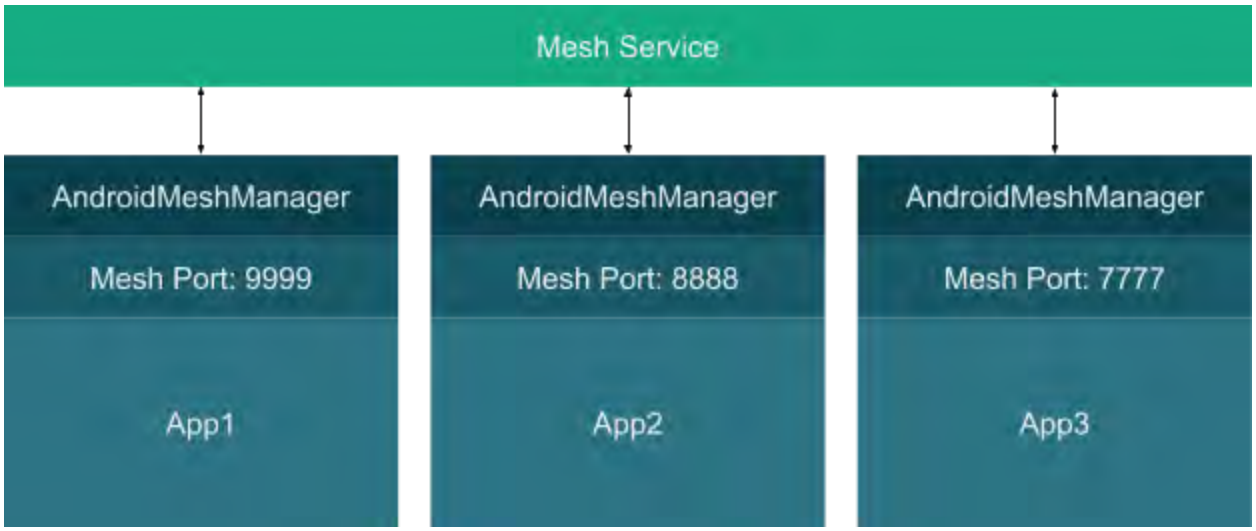


Fig. 12: *Multiple Apps running on the same device, using a common service*

In Figure 13, a mesh with three devices is shown. Notice that device one has three apps running. Apps are only notified of peers which are running the same app (the developer does not get access to all of the devices on the mesh, even though other devices may act as forwarding nodes in order to reach other devices). For instance, App #1, listening on mesh port 9999 will only "see" peers 1 and 3. App #2, will only "see" peers 1 and 2. App #3 will "see peers 1 and 3 as well. Data being sent from peer 1 to peer 3 will be sent through peer 2, even though it isn't running either of the apps that peer 1 and 3 are using.

On Java, RightMesh does not currently support a service environment, so only a single RightMesh app can be run on one computer, IoT device, or sensor at a given time, however it still must bind to a MeshPort as this prevents other apps from sending data to the device, or intercepting data from the device.

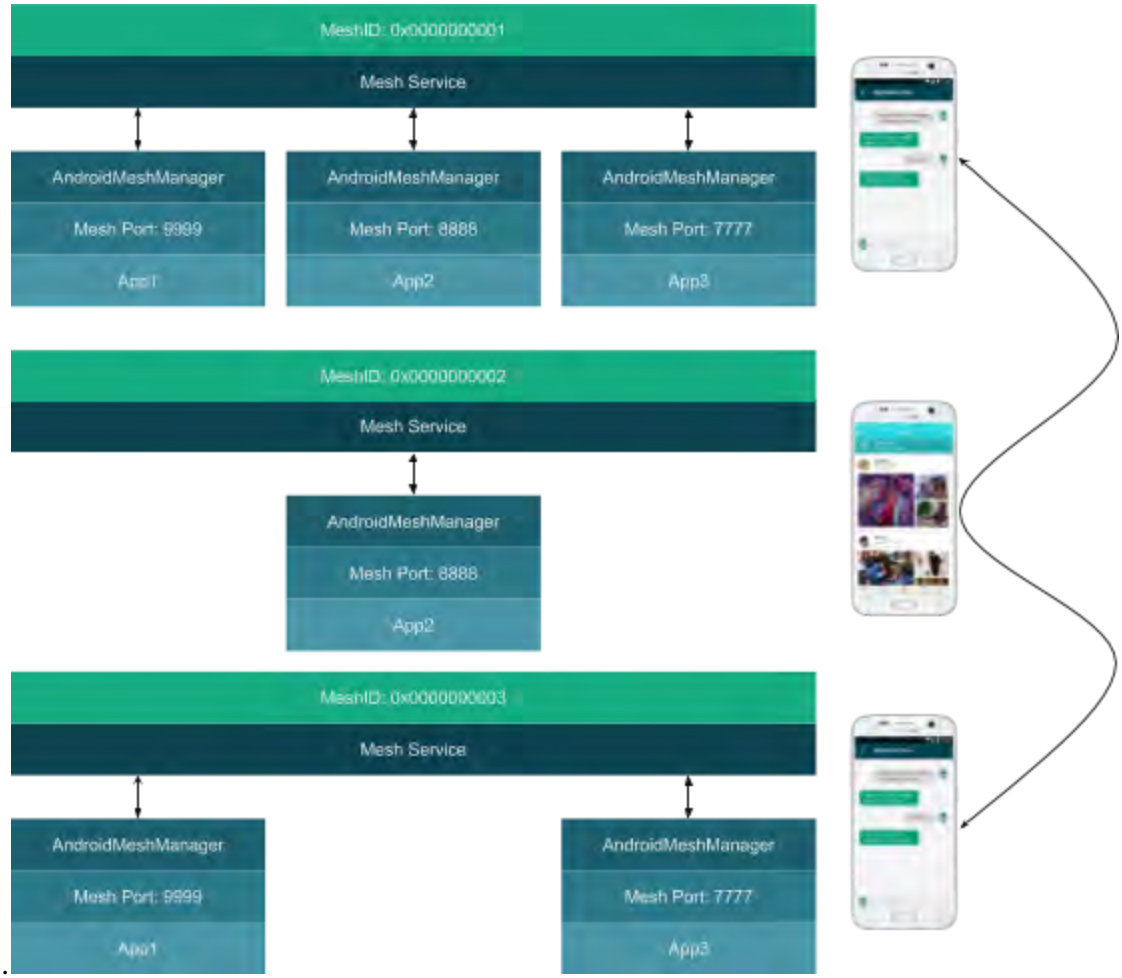


Fig. 13: *Multiple devices communicate through the service, where each phone may have different sets of apps*

Internal roles (MASTER, CLIENT, ROUTER)

Internally, RightMesh labels endpoints of links depending on the role the device is playing within that link. The role depends on the underlying technology (Wi-Fi, Bluetooth, Wi-Fi direct) and how the technology is being used.

Wi-Fi

MASTERs act like traditional network servers and listen for incoming requests and respond to the requests. MASTERs are also key hubs in the topology. A Wi-Fi device operating in hotspot mode would be a MASTER.

CLIENTs act like typical clients and send outgoing requests and wait for responses. They are also able to listen to other requests and responses and process them without necessarily responding. A Wi-Fi client

device would first connect to a RightMesh Wi-Fi hotspot, determine the MASTER IP address using the DHCP gateway and send requests for topology discovery.

ROUTERs are devices which are linking two different sub networks. For Wi-Fi links, this would be a switching device (one which is in range of two or more hotspots / MASTERs). This device would be responsible for communicating topology information about each MASTER subnetwork to all of the other MASTER subnetworks. Functionally, it is similar to a CLIENT device, in that it is operating as a Wi-Fi client; however, it virtualizes its connectivity by dividing the time it stays connected to a particular MASTER and then sending discovery requests to each upon leaving and rejoining other MASTERs.

The connection process in Wi-Fi works as follows. The MASTER devices turn their hotspot on and name the hotspot with a set RightMesh pattern. This lets RightMesh CLIENTs and ROUTERs filter out trying to connect to hotspots which may not be running the RightMesh network. CLIENT devices use blacklisting and manipulation of the Android Wi-Fi configurations settings to force the phone onto a RightMesh hotspot. Once an IP address is obtained, the RightMesh topology discovery protocol starts by sending a HELLO request. The MASTER devices respond to the HELLO request which includes some exchange of topology information. Devices configured with the ROUTER role will act the same way a CLIENT does if there is only a single MASTER in range. As soon as more than one MASTER is in range, the ROUTER device will change from operating as a CLIENT to operating as a switching device, and will change the topology discovery protocol packets it sends. It will also periodically switch between the MASTERs and exchange topology information from each side.

Bluetooth

Roles on Bluetooth work a bit differently as each Bluetooth device simultaneously acts as a MASTER and a CLIENT. If a device has more than one Bluetooth connection, it acts as a ROUTER since it may be linking two separate subnets in the same way our switching devices work. Since our philosophy is that the user should never have to make a pairing with another phone manually, we wanted to use a Bluetooth version on Android that would support connecting without having to agree to pair, or enter a pin. The way we were able to make this work was with Bluetooth 2.0 RFCOMM which is intended for connecting to embedded devices without any input device to provide pairing information on. Android phones are also able to act like a Bluetooth 2.0 RFCOMM device (in addition to connect out to one), which is why they can act as a MASTER or a CLIENT.

On Android, it is possible to support several Bluetooth connections at once. It may be as high as 8 - 10 connections, but in practice it is usually more often that it is 3 - 4. In the case where more than a single connection is possible, the phone can sit listening for incoming connections at the same time it is making outgoing connections.

The connection process for Bluetooth devices is a bit different from Wi-Fi devices since a device can act as both a CLIENT and a MASTER. In one thread, the device acts as a MASTER, which sets the device to be discoverable and listening on one virtual channel. In another thread, the device acts a CLIENT, performing Bluetooth scans. When a scan completes, a list of Bluetooth MAC addresses are provided along with the device names. Similar to the Wi-Fi CLIENTs, Bluetooth CLIENTs can filter out devices that don't have the RightMesh device pattern to avoid connecting to Bluetooth devices which aren't running RightMesh. When making the connection, once the connection is formed, the device acting in the CLIENT role sends a HELLO request to the device running in the MASTER role which responds with topology information.

When a device has made a Bluetooth connection to two or more devices, it changes its role slightly to behave more like a ROUTER. The device still maintains its MASTER or CLIENT behaviour when it comes to determine which device sends outgoing requests and which answers, however, the topology information exchanged changes slightly as multiple networks may need to be linked together.

Wi-Fi Direct

Wi-Fi Direct works almost the same as with Wi-Fi, with a few key differences. Wi-Fi Direct hotspots are invisible to the user (in a normal Wi-Fi hotspot there is an icon in Android that shows a hotspot is running). Wi-Fi Direct hotspots also have the ability to advertise extra data to the Wi-Fi Direct clients. In Android, with Wi-Fi Direct hotspots it is not possible to change the name of the hotspot: it always takes the name DIRECT-<something>. However, we can append information in a hashmap which can be advertised to Wi-Fi Direct clients. In this hashmap, we RightMesh Wi-Fi Direct MASTERs provide a network name similar to setting the SSID in Wi-Fi or the device name in Bluetooth. We also provide the MeshID of the MASTER device.

The biggest difference between a Wi-Fi Direct MASTER and a Wi-Fi MASTER is that a Wi-Fi Direct MASTER can also be a Wi-Fi CLIENT or Wi-Fi Direct CLIENT at the same time. We consider these "outgoing"

connections or CLIENT connections, while the MASTER connections are incoming connections. One important note though, is only one outgoing connection may be made at once, unless a device is running in Wi-Fi Direct ROUTER mode, which would use the switching technology that Wi-Fi ROUTERs use. The reason that MASTERs advertise their MeshID is so that RightMesh can attempt to create a long chain of non-switching Wi-Fi Direct MASTER/CLIENT links. Another thing to note is that a normal Wi-Fi CLIENT cannot connect to a Wi-Fi Direct MASTER, only the opposite direction works. Another important note: a Wi-Fi Direct MASTER can act as a Wi-Fi client of an external Wi-Fi hotspot at the same time, which makes it a good candidate to share external Wi-Fi into the RightMesh network.

Similar to the Wi-Fi MASTER / CLIENT behaviour, the MASTER sits waiting for incoming connections from CLIENTS or ROUTERS. The CLIENT device first inspects the extra information from the MASTER to see if it is in fact a RightMesh MASTER (does it provide the pattern, the MeshID, etc.). It then attempts to associate with the MASTER. Once an IP address is received, it proceeds in the same manner as a Wi-Fi client.

Packet Structure

The packets are defined using Google Protobuf. There were several reasons for choosing this format. According to the project page, it is a "language-neutral, platform-neutral extensible mechanism for serializing structured data". This way, if we decide at a later date to support c/c++ for embedded devices, IOS, or other architectures, it will easily be possible. The only part that would need to be re-implemented is the logic that handles the packet types, rather than having to hand code the packet format as well. The other main benefit is the efficient encoding of the on-wire, or in the RightMesh case, on-air data. There is some early evidence that Protobuf performs much better than for example, JSON. There are also more detailed performance comparisons with other serialization libraries as well. When designing RightMesh, it was well known that we would be using links such as Bluetooth which provide limited bandwidth. Also, in dense deployments, bandwidth will also be a luxury. Further, since the protocol is running on mobile devices, it is important for the phones to be able to quickly parse the packets. So we needed a structure that supported compacting the data, while also processing quickly, which made Protobuf a good candidate. While we are not providing more details on the exact packet structure currently, it is because it is still in flux. Once it is ready, we will collaborate on open standards for interoperability with RightMesh and other partners.

Packet Types and Priorities

RightMesh packets are delivered to the one-hop neighbours using priority queues. Each one-hop link has its own set of priority queues. For instance, a device connected to a peer with both Wi-Fi and Bluetooth would have one set for the Wi-Fi link and one set for the Bluetooth link that are independent of each other. First, the highest priority queue is emptied. Then, the next priority proceeds one packet at a time, with a check for a higher-priority queue not being empty. If a higher-priority queue has packets, the higher-priority queue is emptied and then the lower-priority queues are served in priority order.

Acknowledgement Packets (ACK)

The highest priority queue is ACK. These are one-hop acknowledgements of control packets (and often contain topology information in them), DATA, and DATA_ACK packets. The reason for making an ACK the highest priority is that if other control packets or data packets are sent in high numbers at the same priority, they will overwhelm the ACKs—potentially causing even more control or data packets to be issued.

Control Packets (HELLO, GOODBYE, JOIN, LEAVE)

There are HELLO packets which are used to indicate a device is still connected to (or joining) the mesh using a CLIENT link, and to request topology information from a MASTER side of the link. GOODBYE packets can be sent from any role type and indicate that a device is going to leave the mesh. JOIN packets are used to link together two or more separate sections of mesh together (for instance, linking two hotspot networks together). These are sent by ROUTERs, Bluetooth, or Wi-Fi Direct links which are linking together sections (in either MASTER or CLIENT link role). LEAVE packets are used to indicate a switching ROUTER link is about to temporarily LEAVE one section of mesh and JOIN another. In all of these cases, MASTER sides of the link are responding with the ACK packet containing particular topology information.

End-to-End Data Acknowledgement (DATA_ACK)

The next priority after ACKS and control packets, is DATA_ACKs. These are a special type of ACK—which is an end-to-end ACK that is sent from the final destination of the packet and potentially multiple hops away from the source. Again, if these don't take a higher priority over DATA packets, the data transmission protocol may flood the network with DATA packets, causing the DATA_ACK to be lost when actually the

DATA has arrived successfully, leading to unnecessary retransmissions. We give the DATA and DATA_ACK packets lower priority from control packets because if these packets overwhelm the topology signalling, it will cause devices to think entire connections have broken, or updates about connectivity will get ignored when devices are sending high throughput data through the network. More details regarding when DATA_ACK packets are sent are provided in the *Data Transmission* subsection to follow.

Peer Discovery and Mesh Formation

The peer discovery process is used to discover local topology of the mesh so that the RightMesh service knows which nexthop peers may be used to route data packets to the appropriate destination in the network. This section will describe the RightMesh peer discovery protocol that allows a mesh to form over a complex set of roles defined earlier in the document. There are two ways in which this can be implemented practically. The first is where the users of RightMesh apps manually set the roles and link types which should be active (called manual mode). The second is autonomous formation which will be described in the following subsection. The remaining discussion in this section will assume that roles have been assigned either manually, or via autonomous formation.

Challenges and Fundamentals to Forming a Mesh

One of the biggest challenges in forming a mobile mesh network with smartphones is finding ways in which to link hotspots together. Recall from the role section that it is not possible to be a Wi-Fi hotspot and simultaneously be a client of another hotspot. One way to link hotspots is with Bluetooth. This requires the two hotspots to be fairly close to each other (often the Bluetooth range is lower than Wi-Fi).

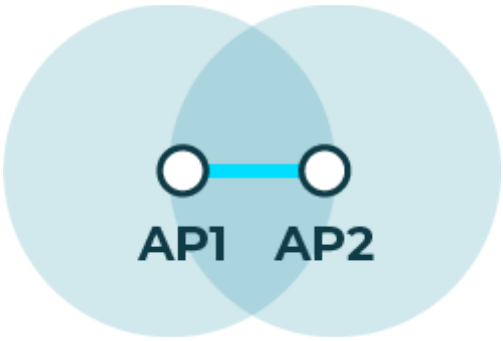


Fig. 14: *Two Access Points (hotspots) connected via Bluetooth.*

In Fig. 14, the circles represent the coverage of the Wi-Fi hotspots, and the blue line represents a bluetooth link between the APs. In most practical cases, the two devices would need to be closer to each other than illustrated in the figure since bluetooth range is usually shorter than Wi-Fi range.

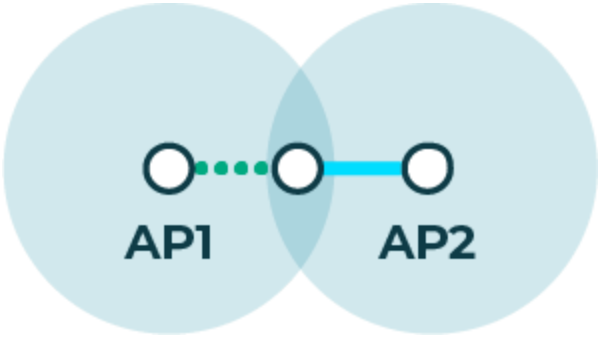


Fig. 15: *Linking two hotspots with an intermediary device using bluetooth and Wi-Fi together*

Figure 15 shows a method to link together two hotspots using a third device which is connected to AP1 with Wi-Fi and to AP2 with bluetooth. This is because even though it is in Wi-Fi range of both, it can only be a client of one hotspot at one time. This also extends the distance between the two hotspots as well. These methods are used by many competitors.

There are a few limitations to these approaches. First, Bluetooth links often have much lower bandwidth available compared with Wi-Fi. For instance, Bluetooth 2.x uses 1Mhz channels, while 802.11 typically uses 40Mhz or more. Also, if the Bluetooth channel selected by Android overlaps with the Wi-Fi channel either of the hotspots are using, there will be significant interference causing the bluetooth link to perform even worse. It is not possible in Android to control the Wi-Fi hotspot or Bluetooth physical channels.

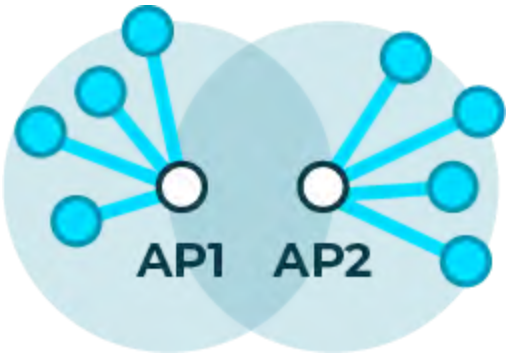


Fig. 16: *Two Access Points (hotspots) which cannot form a Bluetooth connection because they already have too many other Bluetooth devices connected.*

Furthermore, it may be possible that if devices arrange themselves in the incorrect manner, there may be no Bluetooth channels available to link together the hotspots, resulting in a partitioned network that can never form a mesh. This is illustrated in Figure 16.

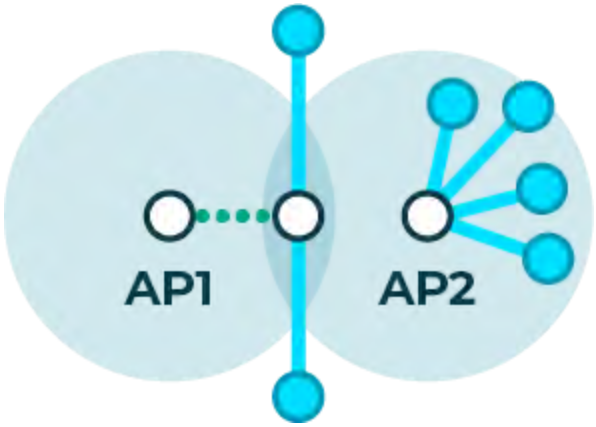


Fig. 17: *Another scenario where the critical link is unable to form*

Figure 17 shows another example where the critical Bluetooth link may not be able to form due to other connections already being established. In both of these examples, a critical topology pattern is required whereby links interleave Wi-Fi and Bluetooth. This also introduces a critical bottleneck into any long path: all paths longer than a couple of hops will always be limited by the bandwidth available via the Bluetooth links.

Another method which can be used to solve some of these problems is the use of a switching device which uses time division to multiplex between two or more hotspots at any given time. This is an approach we filed a US provisional patent to cover. This is illustrated in Fig. 18 whereby two hotspots which already have maxed out their Bluetooth connections can still be linked together with a Wi-Fi device in range of both, switching periodically between the two.

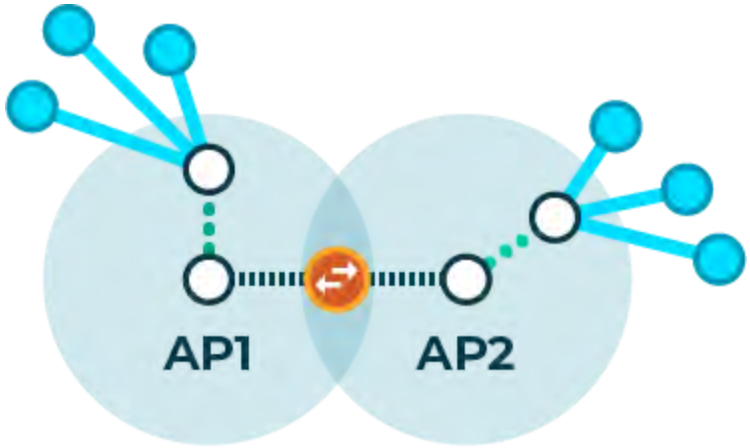


Fig 18: *Two hotspots with many Bluetooth connections connected to each other via a Wi-Fi switching "ROUTER"*

This approach also has drawbacks - the biggest one is that it introduces significant delay for every switching device in the path. At best, it takes 200ms to perform the switch. However compared to the limited bandwidth of Bluetooth links, it may be possible to push enough data on the periodically connected link to achieve higher overall throughput with increased delay. Strategies for routing can then be developed such that Bluetooth paths are taken for low-throughput, low-delay applications, and these switching paths are taken for higher-bandwidth, more-delay-tolerant applications.

Another approach to mitigate both of these limitations is Wi-Fi Direct or Wi-Fi p2p. Recall from the roles section that Wi-Fi Direct hotspots can also simultaneously connect to one other Wi-Fi hotspot, or Wi-Fi Direct hotspot (but never more than one at once, unless using a time division switching approach). This is illustrated in Fig. 19. Note, while a Wi-Fi Direct hotspot can also be a client of a Wi-Fi or Wi-Fi Direct hotspot, a normal Wi-Fi hotspot cannot be a client at the same time.

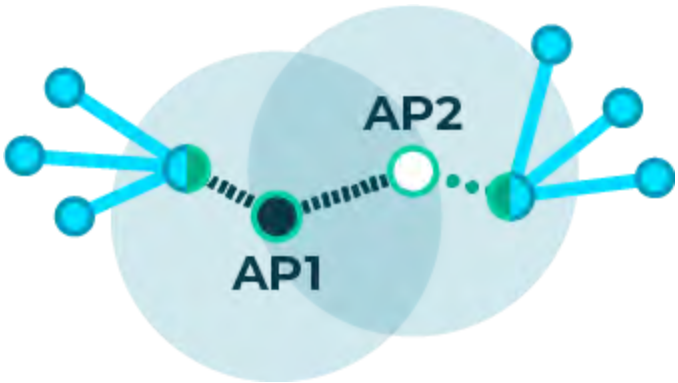


Fig. 19: *AP1 is a WiFi Direct hotspot and also a Wi-Fi client of AP2 which could be a Wi-Fi Direct hotspot or a normal Wi-Fi hotspot*

The key to keep in mind with Wi-Fi Direct is that it is beneficial to create as long of a chain of Wi-Fi Direct links as possible without loops since only one outgoing connection is possible. This is illustrated in Fig. 20. Note that if AP4 were to connect as a client of AP1, it would close the loop making it impossible to connect to an AP5 if it existed. RightMesh has built in some mechanisms to prevent loops from forming in the topology to prevent this.

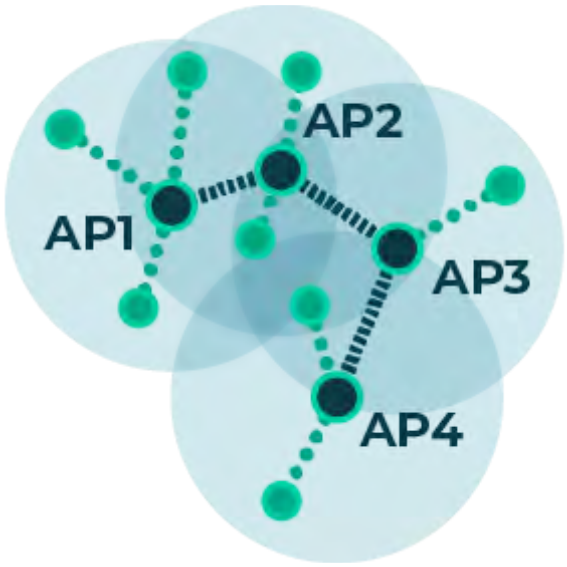


Fig. 20: *A backbone of Wi-Fi Direct hotspots as clients of other Wi-Fi Direct hotspots.*

While some competitors support at most one or two of these methods above, **the real power of RightMesh is that it supports all of these methods simultaneously.** It gives path diversity to provide multiple paths between two devices. Having multiple paths can be extremely useful, and is what forms an actual **mesh**. Multiple paths allow splitting data across multiple paths in order to achieve higher throughput than any one path could achieve on its own. It also allows operation of a redundancy mode whereby the same data is transmitted simultaneously across multiple paths. This way, even if there are losses on some paths, the data is more likely to get there reliably. There are techniques that are in between both of these that are possible. An example of one of these mixed topologies is shown in Fig. 21.

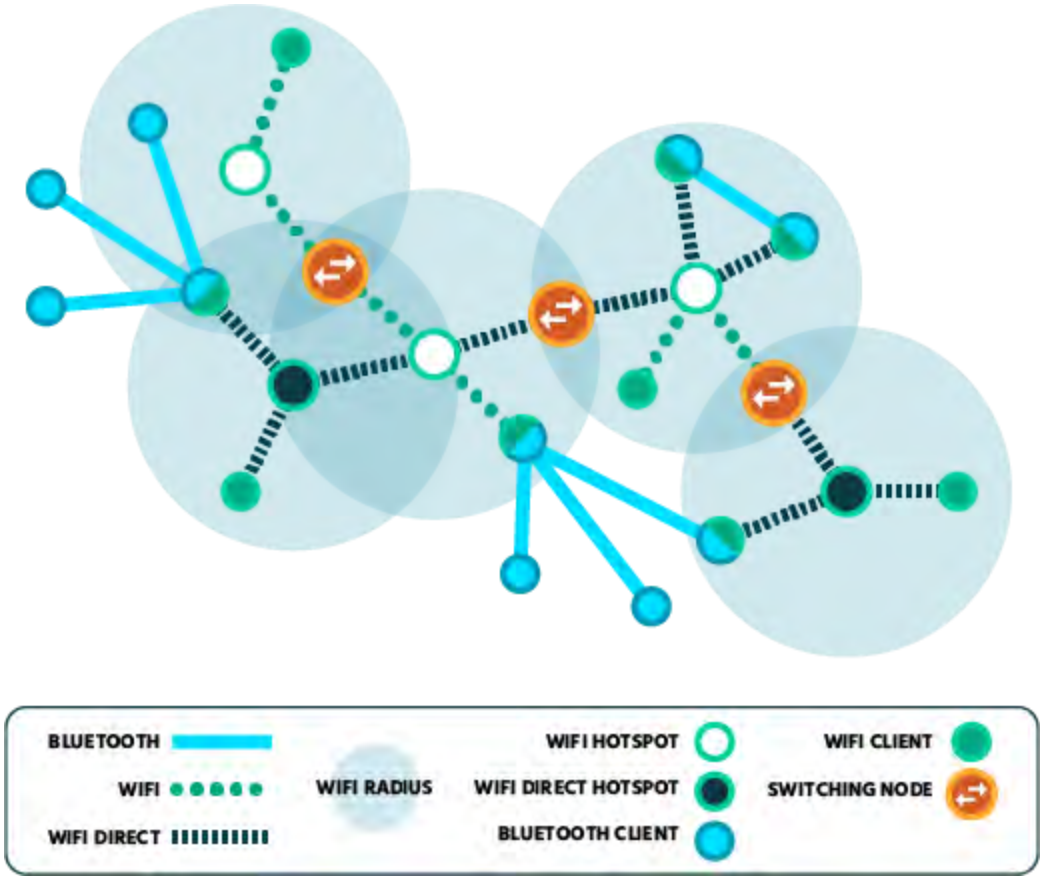


Fig. 21: *A RightMesh network topology made of Wi-Fi, Bluetooth, and Wi-Fi Direct with multiple paths available.*

Wi-Fi Discovery

Assume that a mesh has not yet formed, and there is one MASTER and one CLIENT device nearby each other using Wi-Fi. Recall the MASTER would be operating a hotspot and the CLIENT would be attempting to associate with the MASTER. Currently in Android 7.0 or less, when the hotspot has been created programmatically by RightMesh, it also causes a DHCP server to startup which provides IP addresses to connected clients (there is a well-known bug which we have been working at with the Android developer community to solve in 7.1 and higher where Android has changed the underlying software resulting in a DHCP server not running or giving out addresses to clients in the same way). Once the CLIENT associates and obtains an IP address from the MASTER, it automatically sends a HELLO packet with its own MeshID (Fig. 22). The HELLO packet contains a number of fields such as the protocol version (this way as the protocol advances compatibility may be maintained), the role of the device, and any MeshPorts the device is listening on (this is used to generate PEER_CHANGED events for particular apps that may exist on other devices in

the mesh). For instance, if the MASTER has an app listening on MeshPort 9999 and the client also has an app listening on this port, a PEER_CHANGED event will be generated in that particular app so that the app knows a peer has joined the mesh using the same app. If the MASTER device had another app listening on MeshPort 8888, that particular app would behave as if it was the only device on the network at this point in time (until another device joined with the app listening on MeshPort 8888 as well, or the CLIENT also started an app with MeshPort 8888).

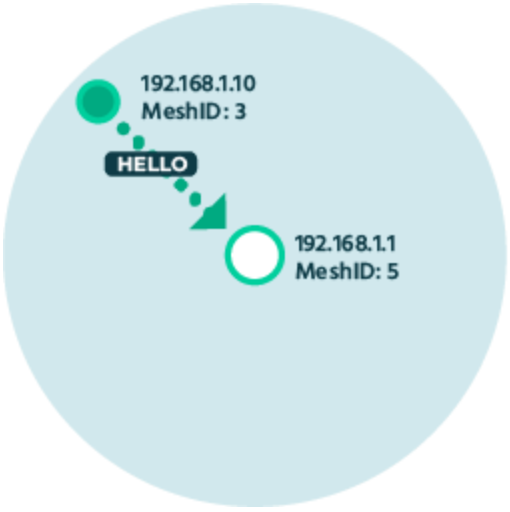


Fig. 22: *A CLIENT (3) immediately after association with a MASTER (5)*

The MASTER adds the CLIENT to its internal routing table, along with the device role, MeshPorts and the IP address of the CLIENT. IPv4 and IPv6 are treated as two different physical links since some Android phones support only IPv4, and others support both. The MASTER responds back with an ACK of type HELLO, with the MASTER MeshID, MASTER MeshPorts, and no additional peers, since there are no other devices in the network yet (Fig. 23).

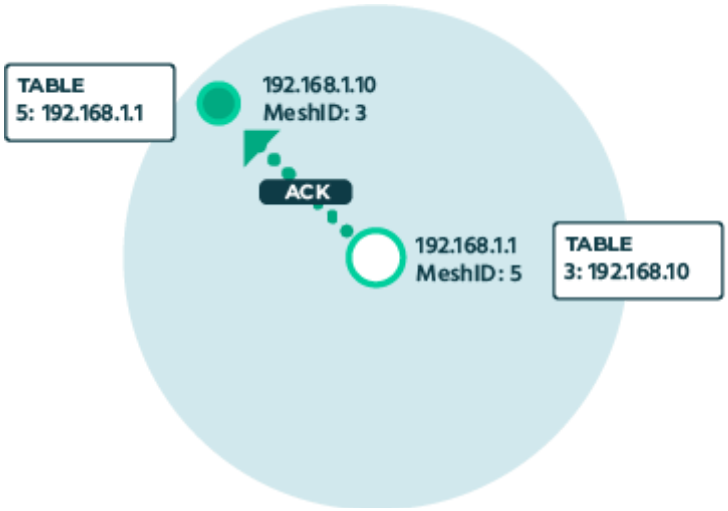


Fig. 23: *Simplified routing tables at the MASTER and CLIENT immediately after the CLIENT receives the ACK:HELLO from the MASTER.*

When the CLIENT receives the ACK of type HELLO from the MASTER, it adds the MASTER to its own routing table. Note: if the CLIENT sends several HELLO packets to a MASTER and receives no response, or a malformed response, it is likely that MASTER is either not actually a RightMesh MASTER, or it is not behaving correctly. In this case, the CLIENT can blacklist the Wi-Fi MAC address of the particular MASTER to prevent being stuck associated with a MASTER which is not actually a valid RightMesh device.

Assume another CLIENT associates with this small hotspot network (which is still not yet a mesh). Again, the CLIENT sends a HELLO request immediately after obtaining an IP address from the MASTER (Fig. 24).

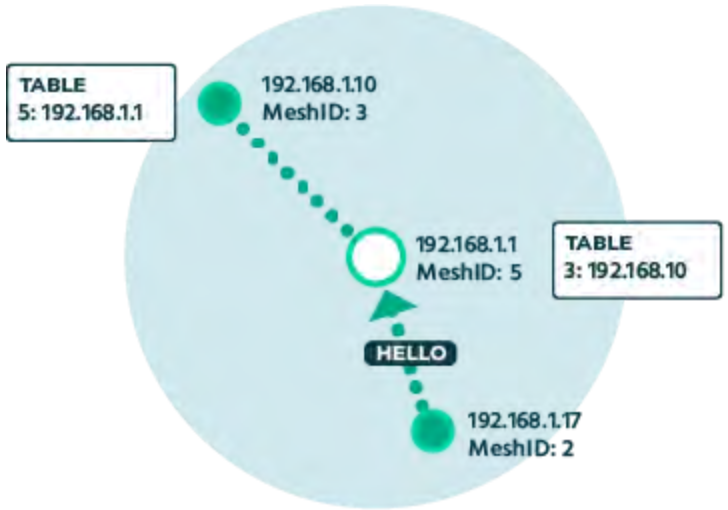


Fig. 24: *A second CLIENT joining the network*

When the MASTER responds, it attaches all of the peers it knows about, which will now actually contain one peer in it. When the second CLIENT (2) receives the ACK and adds the peers to its table, it only records the IP address for the MASTER. For the peers it receives attached to the ACK, it adds the nexthop instead, which is MeshID (5) in this case (Fig. 25).

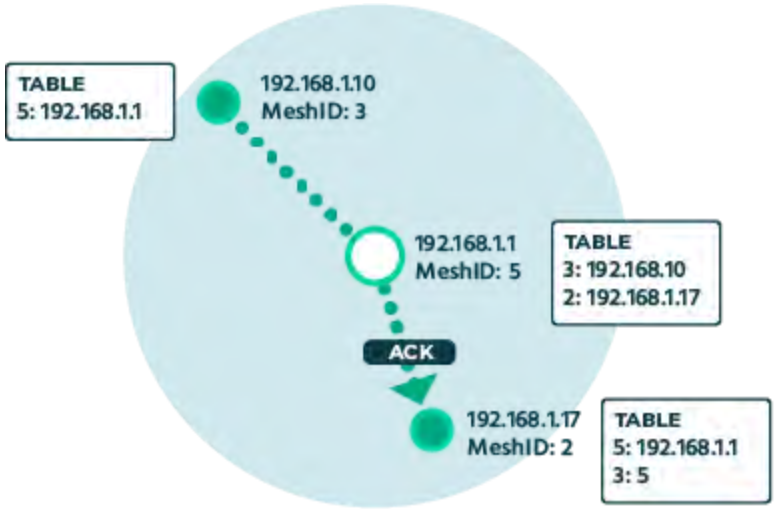


Fig. 25: *After an ACK from the MASTER to the CLIENT after a HELLO packet.*

Notice in Fig. 25 that MeshID(3) has not received the ACK yet, so it does not know that MeshID(2) exists in the network yet. There are two methods for this discovery to occur. With unicast ACKs, it requires that CLIENTs periodically send a HELLO packet to continually discover updates. The other option is local broadcast ACKs. In this case, when the MASTER responds to the HELLO request, it responds with a broadcast that all connected clients could use to update their known peers. If no new peers join for some time, the MASTER could broadcast an update to account for peers which have left the network uncleanly (without sending a GOODBYE packet firs).

Linking Wi-Fi Hotspots

So far, all of the topology discovery has only applied in a 1-2 hop hotspot-based network where it is not necessary because IP addressing already handles everything. However, linking hotspots is why we are

proposing this topology discovery. Assume we change the role of device with MeshID(2) in Fig. 25 to be a ROUTER, and that it is in range of two MASTERs.

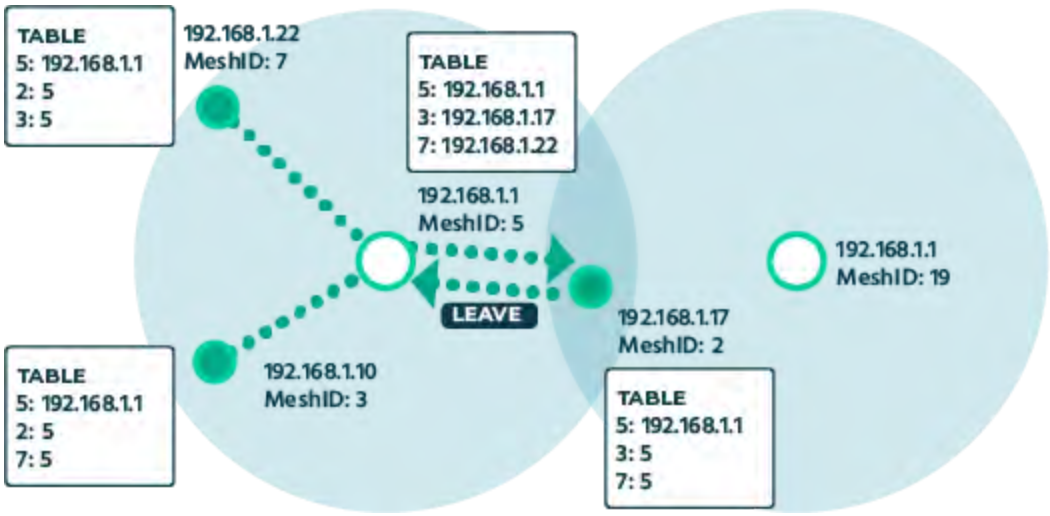


Fig. 26: *Linking together two hotspots to form the beginning of a Wi-Fi mesh*

In Fig 26, MeshID (2) has just detected a second hotspot in range (which would be detected by a second RightMesh patterned SSID). To prepare for leaving to join the second hotspot, the ROUTER device (2) sends a LEAVE packet. This has several functions. First, it requests one final topology update from the MASTER in case devices have joined or left that it has not yet discovered. It also causes the MASTER to mark in the routing table that this particular device is temporarily disconnected. This will prevent DATA and DATA_ACK packets from the upper layers from being queued in the priority queues temporarily. They will be held at the upper layers until this device rejoins. At the lowest level priority queues for the link between the MASTER and the ROUTER, the queues will all be emptied. The ACK for the LEAVE is then enqueued and sent to the ROUTER. When the ACK:LEAVE is received, the ROUTER (2) knows it is free to disassociate from (5) and associate with (19).

Fig. 27 shows the situation immediately after the ACK:LEAVE has been received. Note: the ROUTER also adds the MAC address of the previous MASTER to the routing table as well. This is necessary because it is possible that both MASTERs have the same IP address. Also note, the IP address that the ROUTER (2) obtained from the new MASTER (192.168.1.10) is not the same as the previous IP address it had from the old MASTER (192.168.1.17). One other note is that the new IP address conflicts with an IP address from the old subnet - MeshID (3) also has 192.168.1.10. All of these IP address issues illustrate some of the difficulties in linking

hotspots. An IP address only makes sense in the particular hotspot—there is not translation between hotspots. This is one of the problems this protocol is solving.

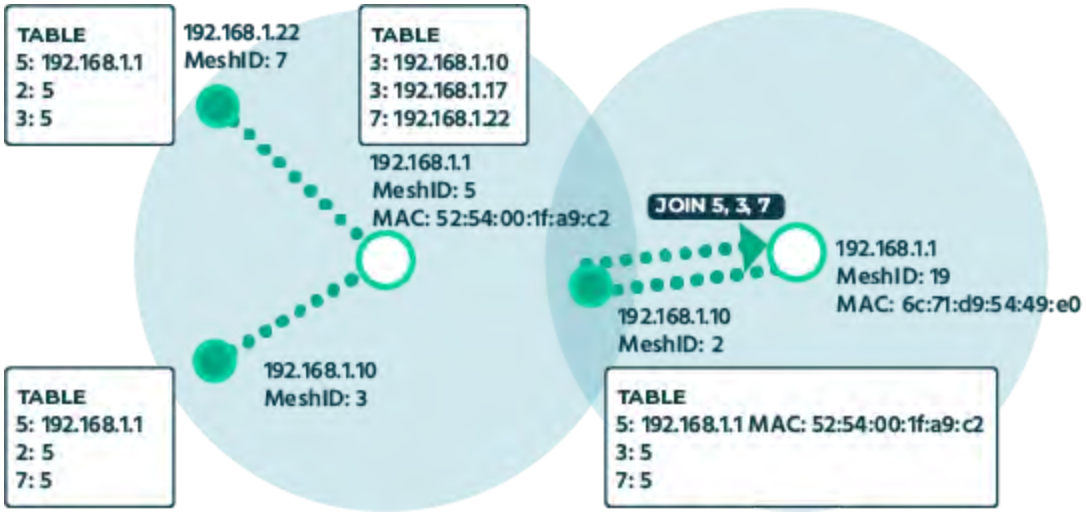


Fig. 27: *Joining two hotspots, after the 1st hotspot has left and immediately after an IP address has been obtained*

Fig. 28 shows the state of the network after the reception of the ACK: JOIN packet at the ROUTER (2). The second MASTER (19) has now learned about all of the devices on the left side of the network. The ROUTER has learned about the new MASTER (and if there were any connected CLIENTs at this point in time, it would also know about them). The left side of the network still needs to learn about the new MASTER. It will require another switch to occur before this is possible. At this point in time, however, the MASTER on the right (19) is able to start sending DATA packets to all of the devices on the left. These packets would be queued at the ROUTER (2) until the switch occurs for them to be delivered. In some early experiments we have found that ROUTERs are able to switch as quickly as 200ms from the time they receive the ACK: LEAVE to when they receive the ACK: JOIN from the second MASTER. The duration with which they remain connected to any particular master is currently bounded between a minimum and maximum time period of up to a couple of seconds, where the actual time connected is uniformly, randomly sampled from within this interval. This could also be updated such that the more the queue fills up, the more likely a ROUTER may switch.

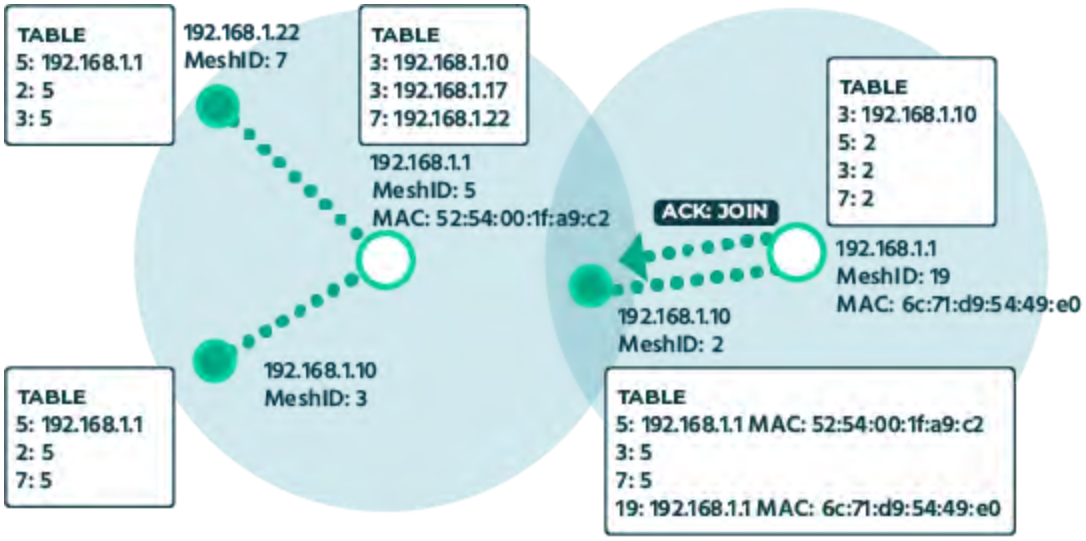


Fig. 28: *After a ROUTER receives an ACK:JOIN from the MASTER*

The state of the network after the ROUTER performs a LEAVE of the right side of the network, and a new JOIN of the left side of the network is displayed in Fig. 29. Notice that the IP address of the ROUTER has changed back to the original IP (depending on if the MASTER gave the same IP. It is also possible that a new IP would be assigned at which point it would be updated in the MASTER table). If the ACK: JOIN is a broadcast packet, all of the CLIENTs learn instantly of the new MASTER (19); otherwise, they will more gradually learn when their next HELLO packet is broadcast and they receive an ACK: HELLO.

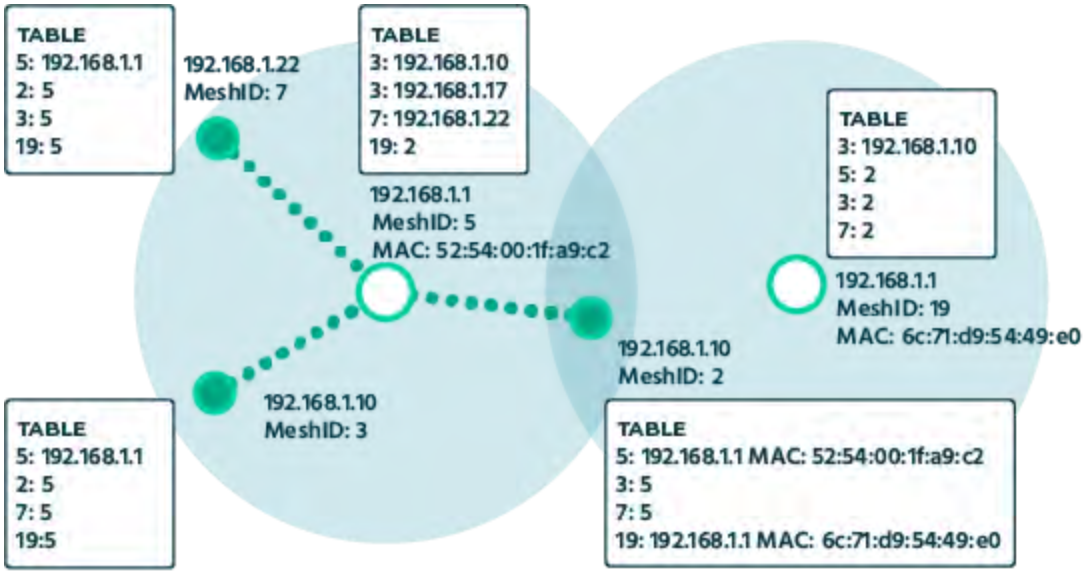


Fig. 29: *After the ROUTER has rejoined the left side of the network*

Bluetooth Peer Discovery

Recall from the role section, that Bluetooth devices operate as both MASTERs and CLIENTs—and in some ways, ROUTERs—depending on if they are making an outgoing connection, waiting for an incoming connection, or if they are linking different sides of a network. More details on how the actual link forms will be provided in *Autonomous Formation*. This section will focus on how the protocol operates assuming the connection has already been made between the bluetooth devices.

In Fig. 30, the bluetooth connection has been established between two phones. Both phones continue to search for other outgoing bluetooth connections and will accept new incoming connections as long as there are enough virtual channels remaining to do so. Immediately after the connection is made, the device which made the outgoing connection (MeshID(5)) acts as CLIENT and sends a HELLO packet to the device which accepted the incoming connection (MeshID(19)).

Fig. 30: *A outgoing connection has been from MeshID(5) TO MeshID(19) using virtual channel 3*

Similar to the Wi-Fi case, the device acting as a MASTER responds the same way. The difference is that on each side, in the routing tables, the MAC address of the Bluetooth devices on each side of the link are recorded. This is so that when there are multiple Bluetooth connections to manage, the device knows which Bluetooth MAC address corresponds to which MeshID.

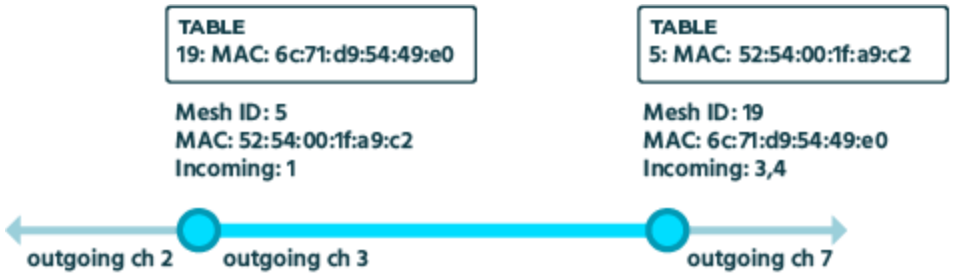


Fig. 31: *After the ACK: HELLO is received by the CLIENT device in the Bluetooth connection*

Linking Together "Bluetooth Islands"

Typically what will happen as more Bluetooth devices join this type of network, the nodes will congeal around devices that are acting as MASTERs. Eventually, there will be some devices that will be both a MASTER and a CLIENT.

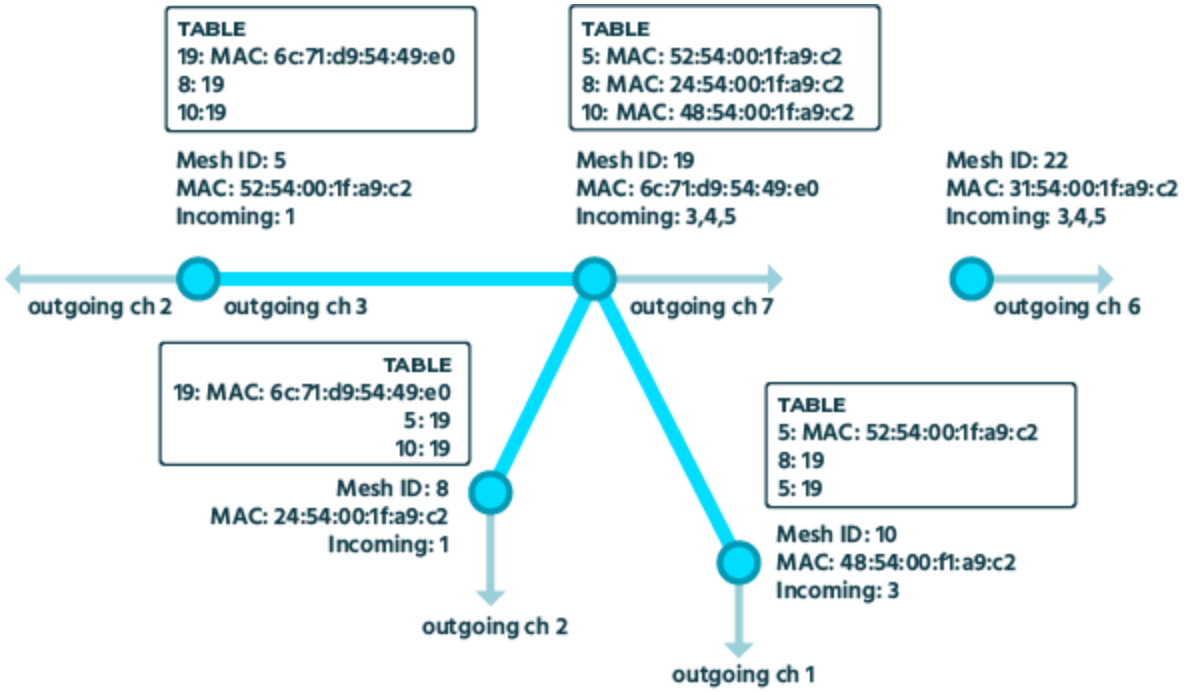


Fig. 32: *A Bluetooth island forming around MeshID (19) - just before it acts as both CLIENT and MASTER*

In Figure 32, a Bluetooth island has formed around MeshID(19). Similar to Wi-Fi discovery, nexthops are recorded as HELLO packets and ACKs are sent during discovery. Eventually MeshID(19) detects MeshID(22) during a Bluetooth scan and has a channel match on its outgoing channel, which will cause it to act as both

a CLIENT and MASTER simultaneously. In this case, it needs to act like a ROUTER since it is operating in both roles together and needs to convey information about its island to a new island.

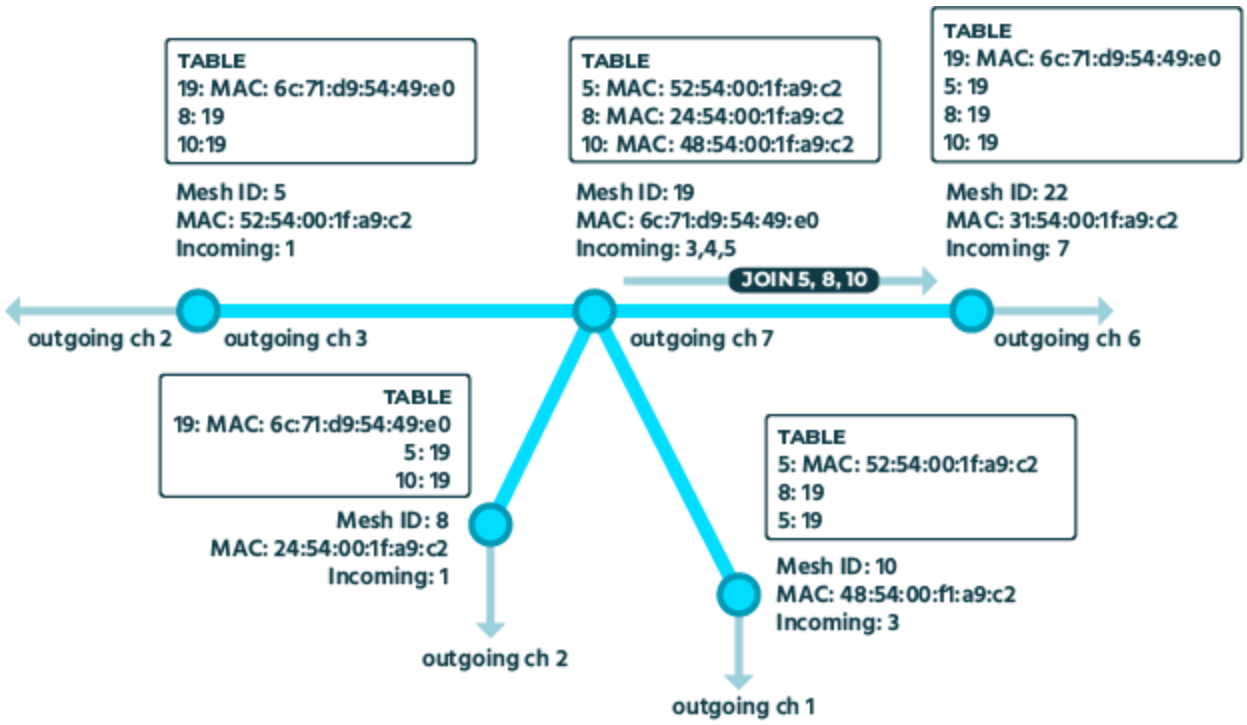


Fig. 33: *MeshID(19) sends a JOIN packet instead of a HELLO packet to convey that the left side needs to be merged with the right side.*

Instead of sending a HELLO packet from MeshID(19) to MeshID(22), in this situation a JOIN packet is sent. This affects what is sent back. Only links which do not share the JOIN source as a nexthop will be returned. This prevents duplicate entries in each routing table where the router is listed as the nexthop. The difference with acting as a Wi-Fi router is that there is no need for a LEAVE packet since switching is not necessary in this linking.

Linking Bluetooth and Wi-Fi Networks

Similar to the case where a Bluetooth devices begins acting like a ROUTER and sending JOIN packets, when a device is acting in both a Wi-Fi role and a Bluetooth role, the Bluetooth link JOIN packets will only be sent to convey the difference from the Bluetooth side to the Wi-Fi side. On the Wi-Fi side, a JOIN packet is not sent.

However, extra peers are added to the HELLO, JOIN, or ACK packets depending on the role of the Wi-Fi link in the case where a Bluetooth link also exists on the same device.

Wi-Fi Direct Peer Discovery

Wi-Fi Direct discovery works as a hybrid of Wi-Fi and Bluetooth. Any devices which are acting as both a Wi-Fi Direct hotspot and either a Wi-Fi client or Wi-Fi Direct client at the same time end up acting the same way as Bluetooth devices in dual roles. If a device has both a Wi-Fi Direct link and a Bluetooth link at the same time, it again changes what peers it appends to the HELLO, JOIN, and ACK packets depending on the role of the Wi-Fi link. On the Bluetooth side, it sends JOIN packets.

Autonomous Formation

The autonomous connectivity layer does the job of assigning internal roles to devices in our network. This decides whether a device will be in hotspot mode or not, which devices to connect via Bluetooth, whether to use Wi-Fi, Wi-Fi Direct, two modes, or all three. In this section, we break down the self-* functionality into the underlying technologies that make up RightMesh one-hop links, Wi-Fi, Bluetooth, and Wi-Fi direct.

Wi-Fi Formation

Consider a network starting completely from scratch with no devices connected whatsoever. With devices using Wi-Fi, the first thing to do is automatically find other nearby devices. This must be done without user intervention. The user should not need to browse for hotspots or setup a hotspot themselves. The first time a user starts up a RightMesh app, they are prompted to allow permissions for Wi-Fi / Bluetooth scanning, location services (which are also required on newer devices for Wi-Fi / Bluetooth scans, and on newer phones, permission to write to the settings - which allows us to change the Wi-Fi settings file (save Wi-Fi networks, blacklist, turn on hotspots). Once this permission is given, RIghtMesh can programmatically turn on / off hotspots and attempt to connect to RightMesh hotspots.

The strategy to make a connection with the first other nearby Wi-Fi device is as follows:

1. Start in either MASTER or CLIENT mode.
2. Remain in this mode for a random period of time bounded by a small maximum wait
3. If a Wi-Fi association is made:

a. If the device is in CLIENT mode, start discovery protocol. If no response after a number of retries, disconnect and blacklist the MAC address of the potential MASTER (Fig. 35). If response, lock mode as CLIENT and continue normal operation.
b. If the device is in MASTER mode a HELLO should be received. If it is not, do not consider the device connected and let timeout occur. If HELLO is successfully received, lock operation as MASTER and continue normal operation.

4. If timeout happens, switch to opposite mode. Every time a switch is issued increase the maximum wait period. (Fig. 34).

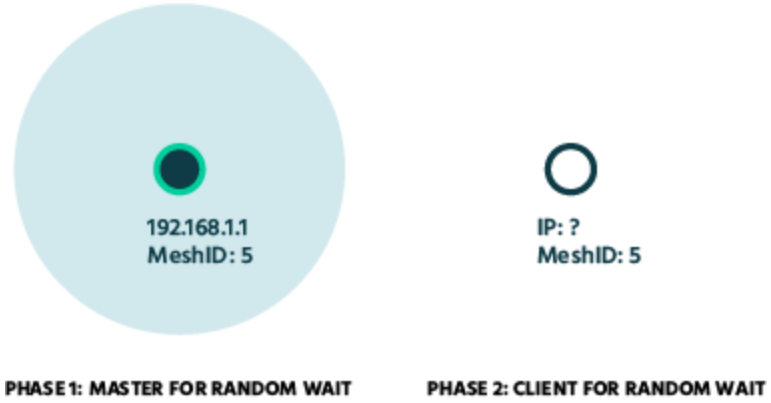


Fig. 34: *Alternately waiting as a MASTER and CLIENT*

Fig. 35: *Avoid connecting to potential MASTERs which aren't operating correctly.*

Once a connection is made, devices which are operating as CLIENTs, have one additional autonomous property. These devices are easily able to continue to perform Wi-Fi scans while they are associated and connected to Wi-Fi MASTERs, while the MASTERs themselves are not. If a CLIENT obtains another MASTER SSID during a scan, the mode should switch to ROUTER mode.

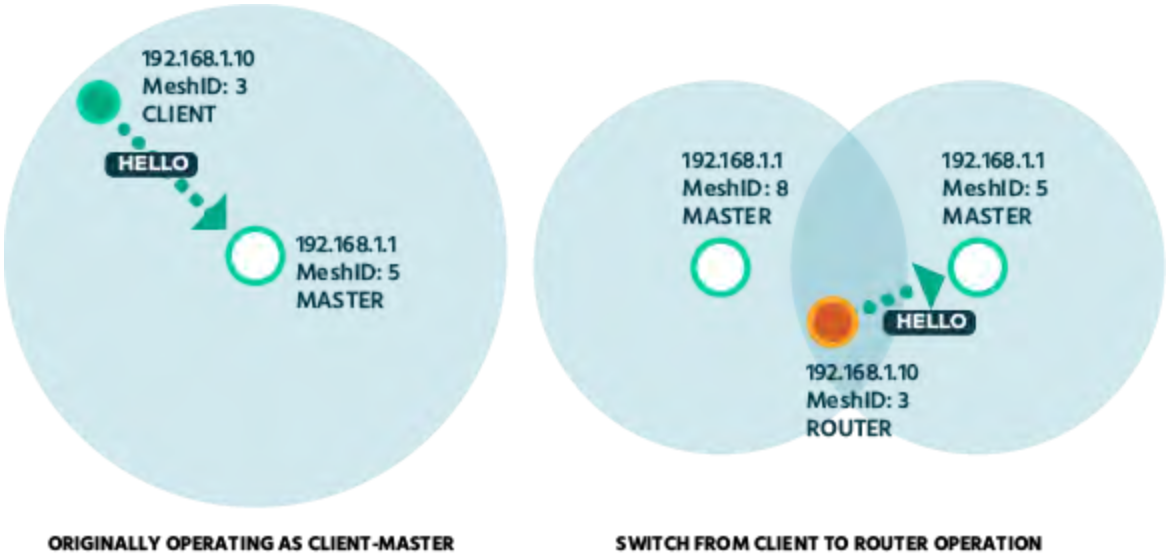


Fig. 36: *Originally operating as CLIENT, detect SSID of second potential MASTER, switch operation to ROUTER*

If a device is in ROUTER mode and there is a failure on rejoining a MASTER, it should switch back to CLIENT mode since it means the MASTER likely moved out of range. This should also trigger removal of the MASTER from its routing table, and the removal of all peers which depend on the MASTER as the nexthop.

Bluetooth Formation

The first stage of making a Bluetooth connection is matching virtual channels (uuids). Currently we use Android Bluetooth 2.0 RFCOMM which requires a fixed uuid (virtual channel). This is used because it avoids needing a pairing process or any user involvement. We assign one of this fixed uuids to each connection. Android seems to support 8 simultaneous connections using this type of scheme.

The biggest issue to tackle is that a device cannot make an outgoing connection with the same uuid it is awaiting an incoming connection on. Further, it cannot use the same uuid twice—once a connection is

established with that uuid it cannot be used again for another incoming or outgoing connection. If two devices nearby are both listening on the same incoming channel, they can't make a connection since the same device cannot make an outgoing connection on the same uuid.

To solve this, RightMesh assigns each device a random uuid to listen for incoming connections on. It continually switches this uuid after some amount of random time so that two nearby devices don't get stuck with the same uuid for listening. At the same time, it is also making outgoing connection attempts on each other possible channel. Fig. 37 shows two devices in the midst of the negotiation process which have not found a match of uuids yet.

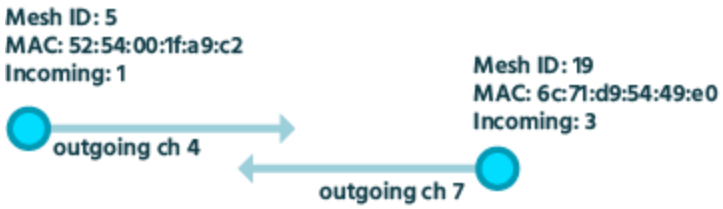


Fig. 37: *two bluetooth devices negotiating uuid connections*

Eventually, the two devices will form a connection when the incoming uuid on one device matches the outgoing uuid of the other nearby device. To prevent a device from being doubly connected and waste an extra set of uuids, we prevent devices from forming both an incoming and outgoing connection to the same device.

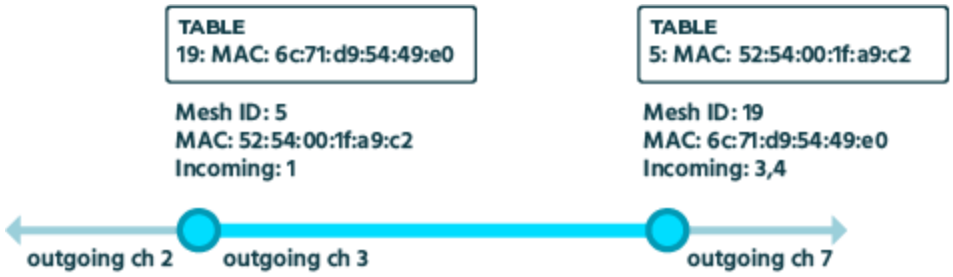


Fig. 38: *Two Bluetooth devices which have made a connection by matching incoming and outgoing uuids*

Fig. 38 shows two devices which have matched uuids and made a connection. After they have made a connection, they continue the process with any remaining uuids left and continue to try to connect to more nearby Bluetooth devices.

Wi-Fi Direct Formation

Wi-Fi Direct formation is very similar to Wi-Fi except switching between modes is not required since a Wi-Fi Direct hotspot can act as a Wi-Fi client as well. As mentioned in the topology discussion, it is very important for Wi-Fi direct devices to avoid creating a loop in their backbone since that will prevent any further Wi-Fi Direct masters from being added without performing switching. This is possible because as part of the discovery process, the Wi-Fi Direct master devices advertise extra information along with the SSID including the MeshID of the particular Wi-Fi Direct MASTER so that Wi-Fi Direct CLIENTs can make a decision about joining before they even attempt to associate.

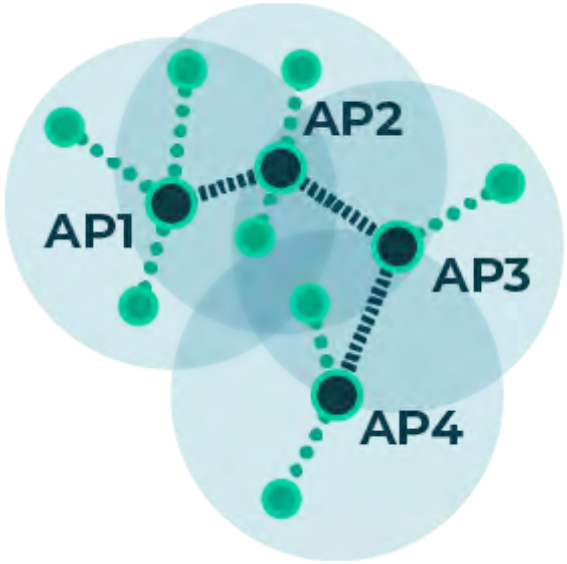


Fig. 39: *Wi-Fi Direct MASTERs which are also CLIENTs avoiding loops*

When it comes to prioritizing which technology should be used in autonomous mode, Wi-Fi Direct backbones should have the highest priority since they offer high throughput and low latency compared with Bluetooth and Wi-Fi switching. After that, the priority is essentially improving link diversity, creating several different types of paths between devices so the failure of one path does not cause the network to partition.

Local Routing

Routing in RightMesh uses a "hopcount" metric presently. This means that in addition to conveying what the nexthop is when the discovery protocol is operating, the protocol also appends the number of hops to reach the destination as well.

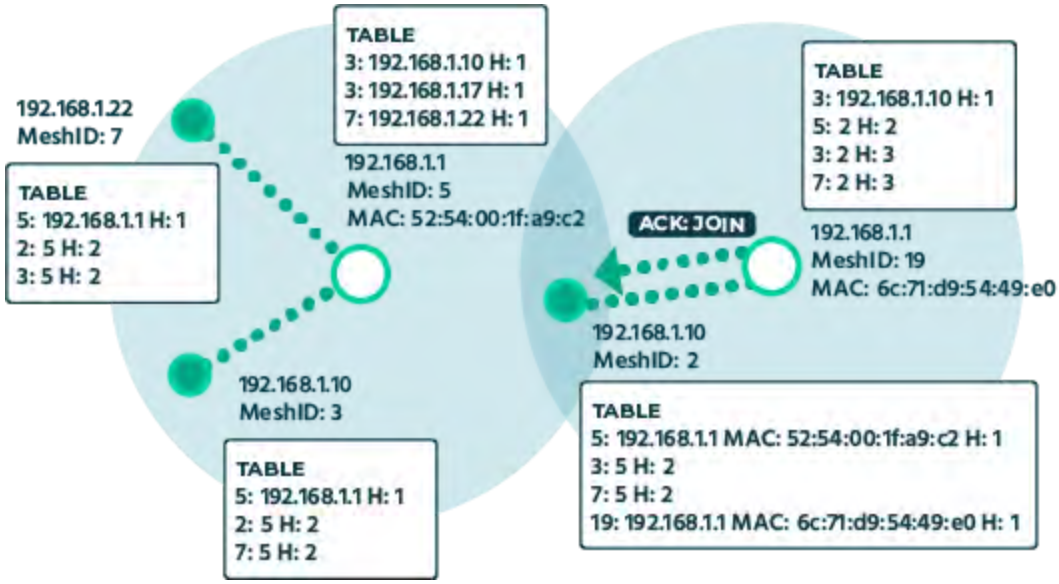


Fig. 40: *An example of a RightMesh network with the hopcount metric included.*

In Fig. 41, a hypothetical network is shown with two possible paths for each node. The routing table with nexthops and hopcounts are showing for the MeshID(1) device. There are two options to go from MeshID(1) to MeshID(3). One path through MeshID(2) which is two hops, and one through MeshID(4), which is three hops. RightMesh would choose the route with two hops.

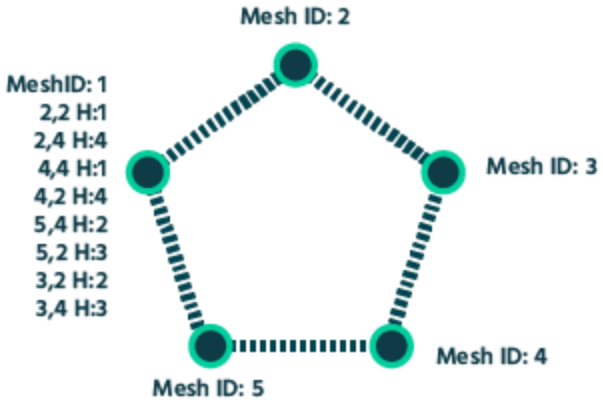


Fig. 41: *A hypothetical network with two paths to each node. The table for MeshID(1) is shown with the nexthop and hopcount shown.*

We recognize this is a naive approach; however, our aim was for bare minimal proof of concept at this stage. It is possible to take into account the underlying link types, delay and capacity constraints, signal strength, and many other factors. This type of optimization is well understood by the networking community and will improve over time.

Data Transmission

Combined with the routing layer and the one-hop connectivity layer, multipath end-to-end reliable communication forms a really unique and valuable part of the RightMesh solution. This is what distinguishes RightMesh from most of its competition. There are a few ways communication typically occurs in mobile meshes:

1) Broadcast to everyone (either using UDP + existing broadcast / multicast approaches, or TCP on a link by link basis - no end-to-end capability)
2) Single-path end-to-end TCP (with many limitations as outlined below)
3) Best-effort UDP communications with no reliability

Many existing mesh approaches simply make use of existing TCP to provide end-to-end connectivity. However, TCP is not well suited to a mobile mesh network for several reasons:

1. Unless rooted, mobile phones do not let the user customize the version of TCP being used.
2. Mobile mesh networks are made of devices that frequently connect and disconnect. When this occurs, a TCP connection would require end-to-end reestablishment of a connection, with a 3-way handshake.
3. With IPv4 It is often impossible to make an end-to-end TCP connection because the IP address in one hotspot means nothing to the neighbours three hotspots away. As such, there is no mechanism to exchange this information between hotspots and have the routing automatically work. In this case, it may be possible to have TCP on each single-hop link, but there are still the same drawbacks from some of the other bullet points to be aware of. In the case of performing TCP on each link, there is still no mechanism to prevent an entire end-to-end path from being saturated with traffic (the congestion control will only work on a link-by-link basis, leaving the queues at the intermediary nodes to potentially overload).
4. TCP often gets interference and congestion mixed up. It may start a backoff unnecessarily thinking that congestion is occurring when it is temporarily poor network conditions due to external factors

(e.g., a vehicle driving through the path of the signal, a microwave being turned on, a tree being between two people who are moving, etc.).

5. The TCP on most non-rooted phones cannot handle multiple paths. This means even if your device has a Bluetooth, Wi-Fi, and Wi-Fi Direct connection available, it is only able to use a single one of them for one data stream. This also applies to Internet connections out of the mesh as well. There are existing versions of TCP that can do this, notably mTCP; however, it is almost never included in commercial phones.

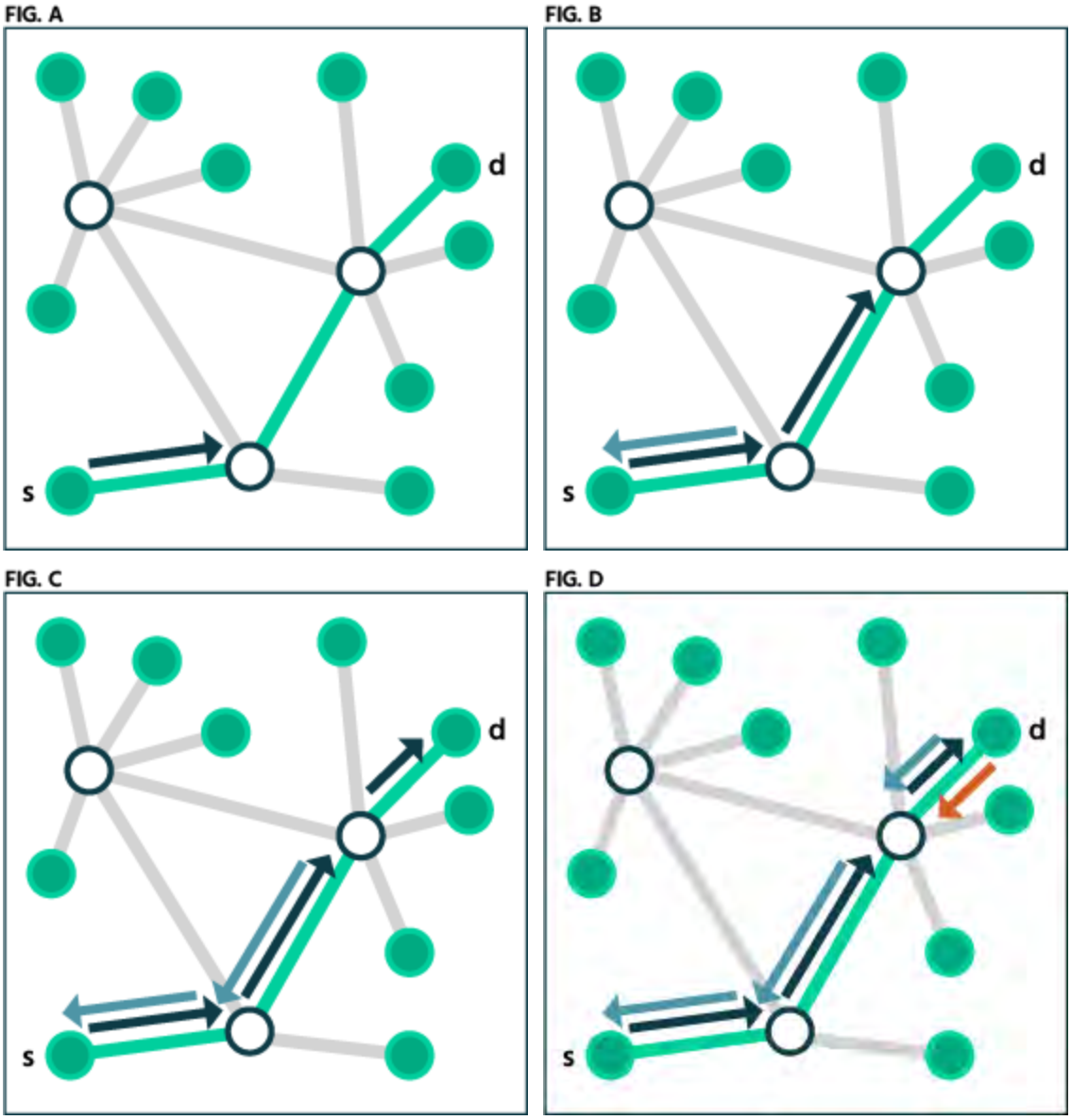
RightMesh uses a combination of end-to-end acknowledgements and one-hop acknowledgements built on top of UDP in order to ensure reliable data transmission. This protocol is based on mTCP and LTP. Since we have implemented our own data transmission protocol, it is possible to split a datastream and send part of it on one path, and part of it on another path, and then have the receiver recombine the packets in the correct order. This would allow higher throughput than any one of the paths might obtain on its own. It is also possible to operate in redundant mode where rather than split the traffic among the links, it is sent across multiple links at the same time.

Keep in mind how the RightMesh packets work. There are DATA packets and DATA_ACK packets. There are also ACK: DATA and ACK: DATA_ACK packets. The ACK packets are one-hop ACKs and the DATA_ACK is an end-to-end ACK packet. There are also single-hop ACKs for the DATA_ACK packet, so the end-to-end ACK is not lost.

Originally, in the proof-of-concept phase, every packet had both a single-hop ACK and an end-to-end (e2e) ACK. This worked reliably; however, the throughput was very low. It was also low because the original protocol waited for the e2e ACK before proceeding to the next packet. We have since improved this protocol in two ways—both based off of lessons learned in traditional TCP.

First, we used sliding windows. We start with a single packet being transmitted. When the e2e ACK is received, this doubles. The next transmision time, two packets are sent. When these two packets are successfully received, four packets are sent in the next transmission, and so on. On the receiver side, e2e ACKs are sent for batches of packets as well and not for every single packet. The ACK specifies the next expected packet. If some packets are received with a missing packet between, the missing packet can be filled in, and then an ACK is sent for the entire group of contiguous packets.

Secondly, there is an adjustable timeout mechanism for backing off when the link becomes congested, similar to TCP.



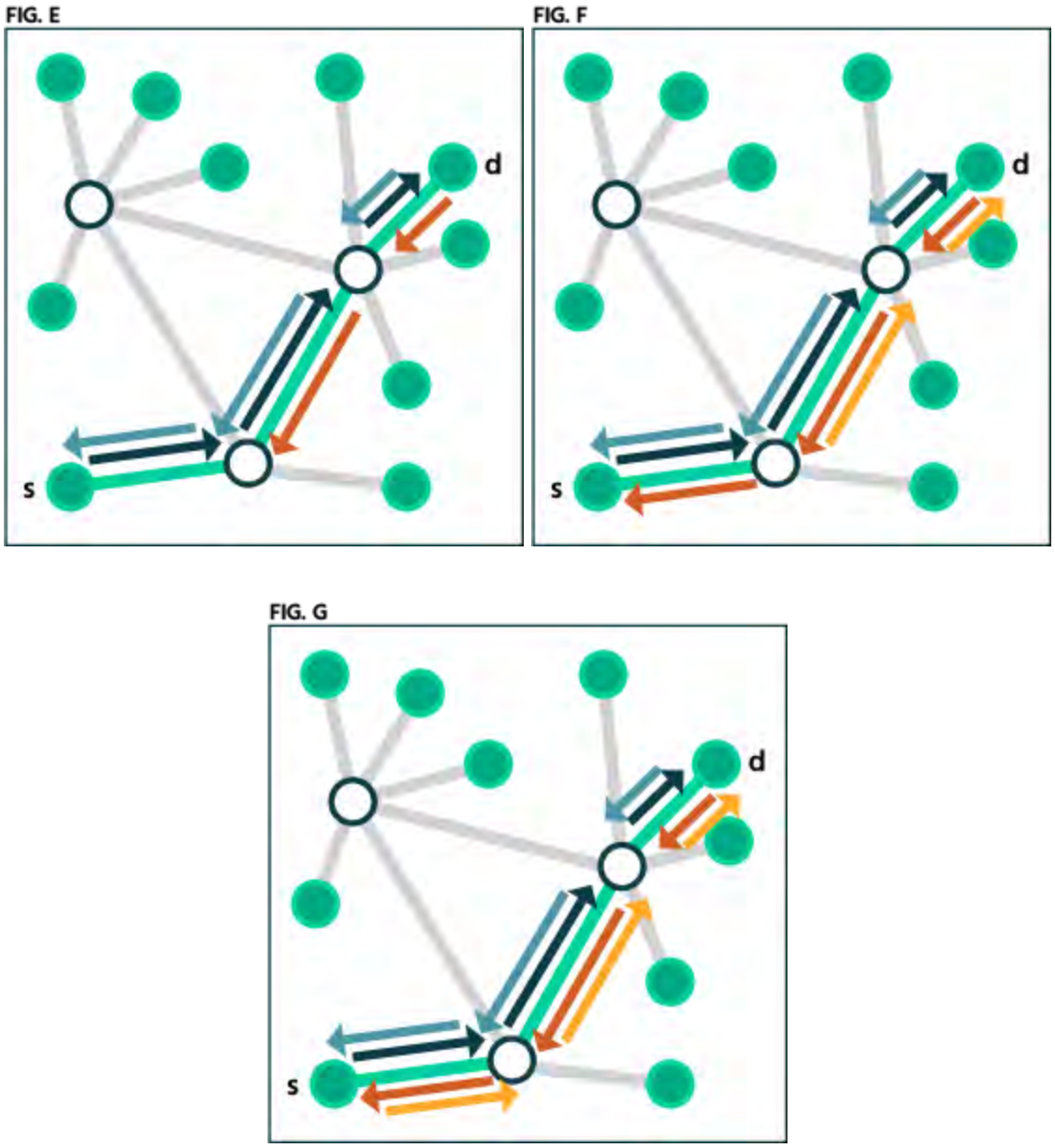


Fig 42 a-g: *One-hop and e2e DATA transmission and ACKs*

There are also some specific modifications that take into account switching devices along paths. Timeout timers are paused when a switch occurs, so the switching does not influence the path timeout. Again, this protocol is still in a proof-of-concept phase; however, the improvements we have been making have improved throughput from the kbps range to the mbps range. Of course this varies with the types of links and the number of hops, as well as the overall load of the network, but this is another area of RightMesh that will improve with time.

Encryption

Rightmesh supports end-to-end encryption using the Open Whisper/Signal library (whispersystems.org). The default library involves a server portion which requires Internet access, so we have modified the library to remove it. RightMesh offer two levels of security: one where the key is directly exchanged in one hop (this is the more secure option). The second, where the key exchange occurs through the mesh over several hops, is less secure because it may be subject to a man-in-the-middle attack.

RightMesh does not store any keys in any server, so any key exchange that occurs securely means only the recipients can decrypt the data. For the company, there is no way RightMesh can be compelled to give up the keys because none are stored. We are working on ways to improve this process (e.g., sending the key split up across multiple paths so that attackers would need to compromise many devices at the same time). We are also working on ways to improve the user-friendliness of a secure key exchange such as with a 2-D barcode or NFC. Compared to other mesh platforms which broadcast to every device, RightMesh only forwards directly on a routing path. As as result, fewer devices have data flowing through them, making it much harder to attack.

Local Multicasting and Broadcasting

There are some competing mobile mesh technologies which take the strategy that it is too difficult to maintain any end-to-end connectivity across multiple hops and aim for more of an opportunistic one-hop p2p technology (and then call it a mesh). It is our view this is less of a mesh and more of a delay tolerant network (DTN). Even among those which do attempt some form of end-to-end connectivity, some take the strategy of broadcasting all data around the network. As mentioned in the routing section, and with the help of the topology discovery protocol, RightMesh is able to compute paths to delivery data through specific devices along the path, rather than a broadcast approach. It is our belief that this will enable RightMesh to be a much more scalable mesh than these types of competitors since broadcasting with only a few devices can quickly overwhelm the capacity available.

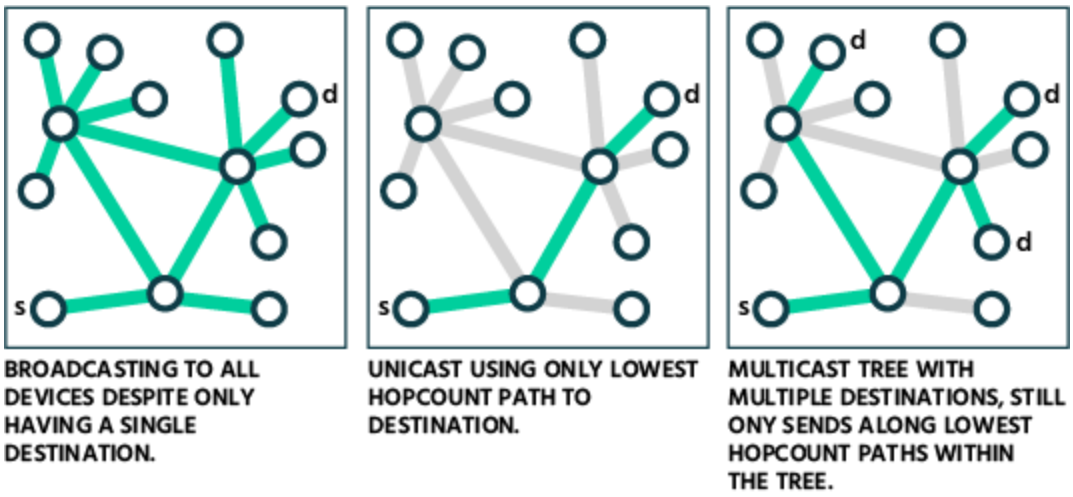


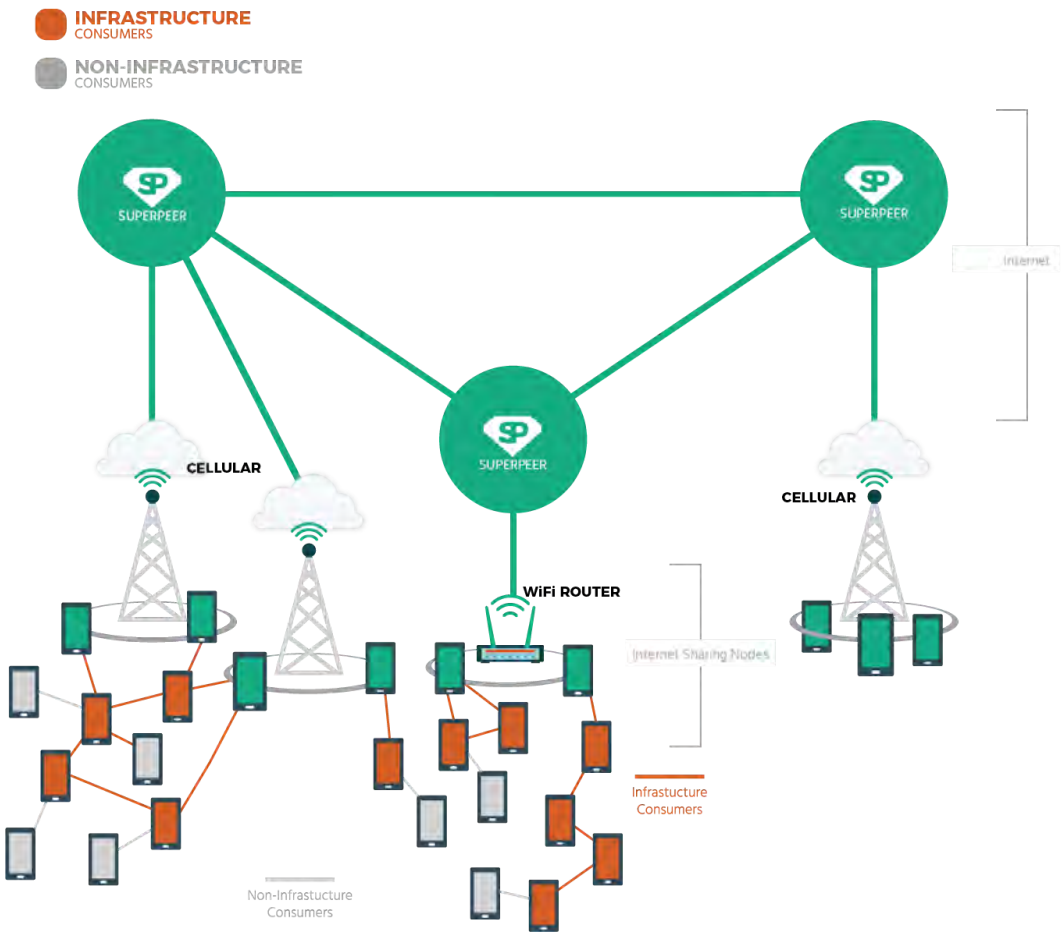
Fig. 43: *broadcast, unicast and multicast*

That being said, RightMesh can support more efficient multicasting and broadcasting in addition to the typical unicast operation that is the default transmission style. Similar to IP multicasting, RightMesh multicasting works by devices joining a multicast group. This allows RightMesh to construct a minimum spanning tree of all of the devices in a group while ensuring the minimum number of unicast transmissions are performed in order to reach all of the devices in the tree, rather than unicasting one-by-one to each member of the group. Fig. 43 shows visually the three different approaches and how the links are used in each of the cases.

4. The Global RightMesh Network

This section will be somewhat briefer than the local connectivity section, but it is not because this is less well developed. Most of the principles that apply to the local connectivity also apply in the global context as well. This section will be used to highlight the key differences and innovations on top of the local connectivity that allow RightMesh to link together two separate meshes across the Internet. The reason for doing this is for a couple of reasons. First, it is unlikely that a mesh across the entire world would scale without involving some infrastructure, particularly at this early stage. There is likely some magic number of hops that a local mesh can support well, and beyond that, we must use existing infrastructure to offset it. Furthermore, in many places—particularly at launch of RightMesh—the density of devices will not support very large meshes. In order to provide some expectation of how people are used to apps working, it should

be possible to use the Internet when it is not possible to make a local mesh with people. Consider a mesh in Vancouver, Canada, and a mesh in Khulna, Bangladesh. We have offices in both places and we may wish to have a mesh chatting app. Imagine how much more useful it would be if the Vancouver office and the Khulna office could communicate within the app, even though there is no way to make a mesh that connects both places without the Internet. We could do this as long as there is at least one person in each mesh who is willing to and is able to provide Internet to the rest of the local mesh.



Adaptations to Autonomous Connectivity in Presence of Internet

When there is a local network only without the possibility of Internet sharing, there is no worry that RightMesh will disconnect from an existing Wi-Fi network; however, in most practical cases, there will always be some RightMesh devices near an existing Wi-Fi network. In this case, the device should prioritize

being connected to the Internet with its Wi-Fi connection. This would mean that the Internet sharing device would only be able to act as a Wi-Fi direct MASTER or a Bluetooth device in order to still participate in the mesh. It would be left up to the user of the device to decide whether or not they would like to actually share their Internet data into the mesh. Even if they did not choose to do so, the device would still be able to maintain an Internet connection and a mesh connection at the same time.

NAT / Firewall Hole Punching

There are often difficulties when trying to connect phones that may share the same Wi-Fi router (using Network Address Translation [NAT]) or that may be on a cellular network which is often firewalled. Cellular companies typically block the phones from listening for any incoming connection. They only allow a connection to be made in reverse of the outgoing connection. For example, suppose you make an outgoing UDP connection to port 5000. It will also open a random high-numbered port to receive a response on. This will function from behind the firewall; however, if you tried to listen directly on port 5000, it would be blocked from receiving anything incoming. Similarly with NAT, there may be the case that both phones are trying to listen on the same port. They would also have the same external IP address, so it would be impossible for both to listen to the same port externally. This would prevent any direct connections to both of them from the outside. This is a well-known problem that has been solved previously by video game companies, chat apps, voice and video communication apps, p2p systems, and many other Internet services.

The way in which we get around these difficulties is with a set of nodes which we classify as Superpeers. These nodes are also running RightMesh, but do so with reliable, stable Internet connections where they have the control to make sure the correct ports are open and available. These Superpeer nodes facilitate the linking of separate meshes by acting as a forwarder between the meshes. These Superpeer nodes keep track of the random, high-numbered port that gets assigned by the operating system of the phones with Internet connections. It performs the mapping of these pairs (port, external IP address) to MeshIDs, so separate meshes know how to reach each other.

Internet Routing vs Local Routing

The biggest change between Internet routing and local routing is extra paths to be maintained. This changes the routing table and the discovery protocol slightly. There is a new boolean field that gets added to the discovery process for peers that indicates whether a peer provides Internet or not. Internet routing still

generally takes the lowest-hop count metric the same way local routing does; however, there are some user preferences that are possible as well. The user may prefer to always use local routing, despite having a lower-hop count Internet route available. They may choose to use the Internet despite having a shorter local path available. Or they may choose the balanced approach which is the lowest-hop count—either Internet or local. Finally, the user may wish to never use the Internet and only use local routing. These preferences may be set by the user in the RightMesh settings which are packaged in the RightMesh service (Fig. 44). These preferences would affect the behaviour of all apps running with RightMesh. Initially, there is no app-level granularity for behaviour when it comes to routing.

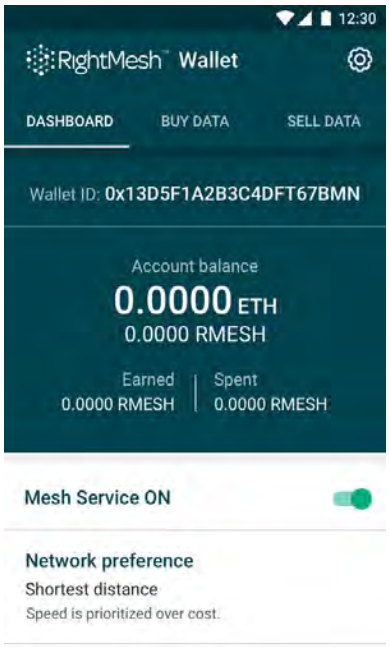


Fig 44: *The bottom of the wallet settings allows setting the routing preferences*

Another change to the routing involving the Internet is the addition of this pair (port, external IP address) to the routing table in the Superpeer layer. Rather than just routing towards the IP address of the Internet Sharing Devices, the Superpeer must also account for the random high port that gets assigned in the case that several Internet-connected devices exist behind the same NAT.

Additional Roles (GATEWAY, SUPERPEER)

There are two additional roles that appear in the routing table with the addition of Internet sharing. The GATEWAY role is assigned to devices when they have—and are willing to provide—Internet access to other

peers in the mesh. When making routing decisions towards separate meshes through the Internet, the RightMesh library looks for routes towards gateways. There may be multiple GATEWAYs which lead towards a single or many SUPERPEERs.

The SUPERPEER role is assigned to devices which provide the hole punching and forwarding capabilities to other devices in the mesh. SUPERPEERs are currently used to determine how to route traffic to another connected mesh. They contain the routing next-hop entries (random high port, IP address, MeshID) mapping. The RightMesh library running on a device within the mesh would need to discover at least one GATEWAY and one SUPERPEER in order to relay traffic to another mesh.

Additional Packet Types (INFO)

INFO packets are used to convey topology information to Superpeers. Any device which is directly connected to the Internet sends these packets to help with the hole-punching capabilities. By periodically sending these packets, it maintains the open state on firewall / NAT for the return direction of the UDP packets.

INFO packets are also sent from any device sending JOIN packets (joining two or more separate sections of mesh together). By having these devices—which are key links between connected "islands"—relaying local topology information to the superpeers, they can make a logical connectivity graph that allows for routing optimizations to occur. This also allows us to debug and troubleshoot bottlenecks and connectivity problems more easily.

Relaying / Caching Behaviour

It is also possible for app developers to provide their own SUPERPEERs. These are special RightMesh Java apps which run on a computer (or cloud instance) which has reliable, consistent, and fast Internet access. In this scenario, the app Superpeer would act as a trusted device that has been trusted only by the app which is making use of it. For instance, an app which allows people to play geocaching may also deploy a geocaching Superpeer. While the app lets people discover geocaching locations, where the location is actually a remote sensor, which relays data into the mesh eventually towards the geocaching Superpeer, where the data may be stored and presented on normal traditional websites. This "data-mule" behaviour is demonstrated in Figure 45.

The app Superpeer would be able to provide some further infrastructure needs that a normal mesh app could not provide. For instance, consider a mesh app where there are remote sensors, but in a location where people occasionally pass (e.g., in the mountains or in northern Canada). An app Superpeer would be used as a collection point where the data would be stored for visualization, analysis, etc., and the RightMesh library would handle routing, despite the phones not always being connected to the Internet. In our remote sensor example, as a hiker passes by, it would forward the collected data the next time the phone had a connection to the app Superpeer through RightMesh automatically.

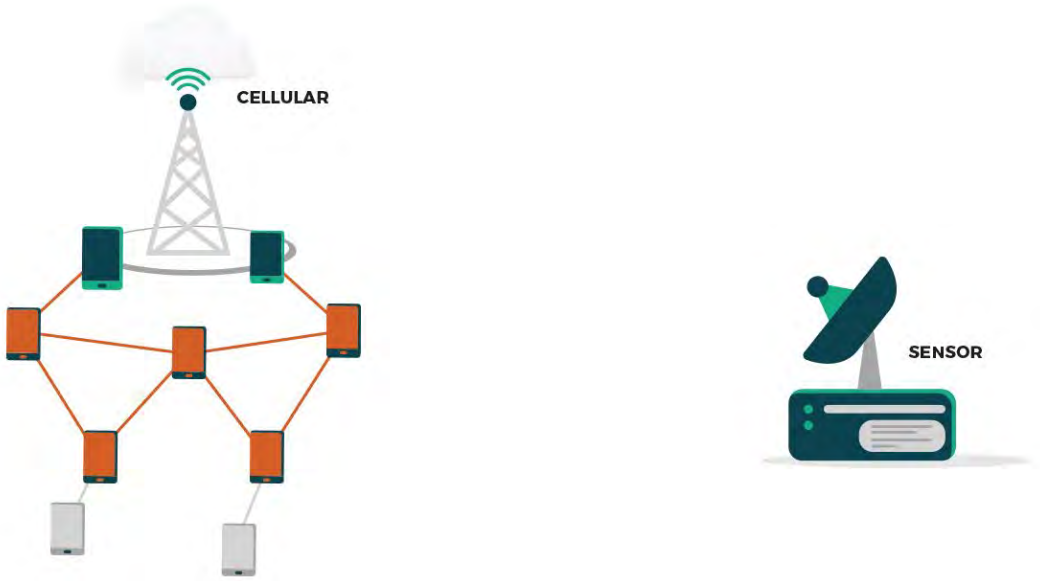


Fig 45: *An example of a data mule application where an out of range sensor uses mobility patterns and caching to relay data to an app SUPERPEER*

Internet Multicasting and Broadcasting

Some interesting possible applications emerge when it comes to Internet-connected RightMesh devices, particularly when involving the Superpeer layer. Consider a device which is running the RightMesh Superpeer layer on an Amazon instance. This device would be partly to support linking RightMesh meshes together and forwarding packets. It could also be running a traditional web server, database server, and other more typically centralized architecture. Suppose this device runs a web service that allows large corporations to push advertisements out to people on apps running on RightMesh.

5. Blockchain/Token Integration

While there have been some technologically strong mesh networks, and even some mobile mesh network frameworks which may prove to be great solutions, there are none which are both technologically strong and provide incentives to users to participate in the network. A user with a monthly data plan may be paying $50 per month for their data, so why would she share it into the mesh for free? Similarly, why should other users leave their Wi-Fi, Wi-Fi direct, and Bluetooth on and connected to other people? Why should people use their battery faster to participate in this network?

Today, we all have grown to trust that ISPs will charge us the correct amount of money for the data we consume; however, there is no real transparent process which lets us see on a granular basis how much data we have consumed from where. Pricing structures are also quite unclear, particularly when roaming, causing some countries and regions to issue maximum fee limits in regulations, or even banning roaming fees all together to prevent consumer gouging.

Any successful mobile mesh should combine strong mobile mesh technology with an ability to support incentives for the network users, providing services critical to the function of the network. This cannot be accomplished with a centralized solution. Otherwise, it risks becoming just another ISP. To fully realize the decentralized vision of a mobile mesh network, it is required that the incentives must be built using decentralized technology.

The RightMesh Token (RMESH)

RightMesh chose to build its RMESH token on top of the Ethereum blockchain, and it is an ERC-20 compatible token. From a technical perspective, while one could use another ERC-20 token within the RightMesh ecosystem, we believed it essential to the user experience of people using the mesh that the payment currency being used to incentivize the technology would be valued based on its utility to perform mesh related tasks.

For instance, suppose someone is using Ethereum to purchase data on the mesh. The value of Ethereum may fluctuate widely during the process of actually consuming the data, so it is very difficult for users to want to spend their Ethereum to purchase data. Ethereum's value is tied to greatly different ideas than those of a mesh network. Ethereum values being able to facilitate and settle transactions, to support some level of

general purpose computation, and some basic messaging with its whisper features. However, it does not consider devices which are remote or intermittently connected particularly well. It doesn't value energy expended relaying data through a network, it doesn't value the price of data geographically, it doesn't value the storage price of a cache on a phone, or it doesn't consider the mobility of a user to transport digital goods to a remote community without reliable internet access. A mesh token would have value tied to all of these factors: the utility of the token within the mesh.

Payment Channels

Similar to "Bitcoin + Lightning", "Ethereum + Raiden" is the comparable micropayment channel solution. Raiden lets two parties set up a channel using the smart contract mechanism in Ethereum whereby two parties create a channel with an initial balance on each side of the channel. As transactions occur, rather than executing the contract, each party exchanges signed transactions, so either party can use these signatures with the agreed upon updated channel balance to close the channel at any point in time in the future. If one party tries to cheat the other, it is possible to produce the signed transaction proving the other party was lying resulting in penalties for the liar. There are still some technical challenges to be solved in the mesh network case, particularly when devices become disconnected from the Internet when a channel is being closed; however, there are solutions such as third-party observer services which can mitigate these risks.

There are some criticisms of Ethereum + "Lightning-like" networks like Raiden, but this is a misunderstanding of how to design these solutions. In the example of an AirBnB or Uber running on Ethereum + Raiden, the customers would establish a payment channel between themself and the decentralized organization, which would act like a payment hub. You would then load Ether or Tokens into the payment channel, sort of like a gift card. This would be the only transaction. You could conceivably pay for rides many times before you had to reload. All of this could occur without the channel being closed. The driver would only close their channel when they want to extract Ether or tokens — maybe once a month like a pay cheque — or less often if they wanted to conserve the fees.

In the RightMesh case, you can have many, many transactions occurring in the channel. When a buyer of data runs out of tokens in the channel it is fairly cheap (compared to re-establishing a channel) to reload the existing channel. The only person motivated to close is the seller; however, there may be creative solutions to avoid channel closing even on the seller side.

RightMesh Token Incentivization System Architecture

Managing limited resources is a known hurdle for RightMesh, whether in regards to battery life, network capacity, or memory and storage limits. Because of these constraints, it is currently not feasible to run a full crypto node on the mobile phone itself.

Since devices on RightMesh have an identification based on an Ethereum account (including the private and public key), using the Ethereum-j library, it is possible to generate signed transactions from the account and pass them through RightMesh to devices reliably and permanently connected to the Ethereum network. We call these devices token SUPERPEERs since these devices are running both the RightMesh library and providing the SUPERPEER layer, and running the the full Ethereum node which enables our Token to operate (or at least are passing the transaction from the mesh to another Ethereum node using IP networks). The benefit of this is that none of the RightMesh devices need to worry about finding the Ethereum network from within the mesh. It is built into the discovery protocol. SUPERPEERs will just appear in the routing table within the library. App developers do not need to even know of the existence of any of this: they only deal with peers, whether they are local, or across the Internet. The reason we distinguish the token SUPERPEERs is because it is also possible to have devices which run the SUPERPEER functions of hole-punching and internet relaying without providing incentivization.

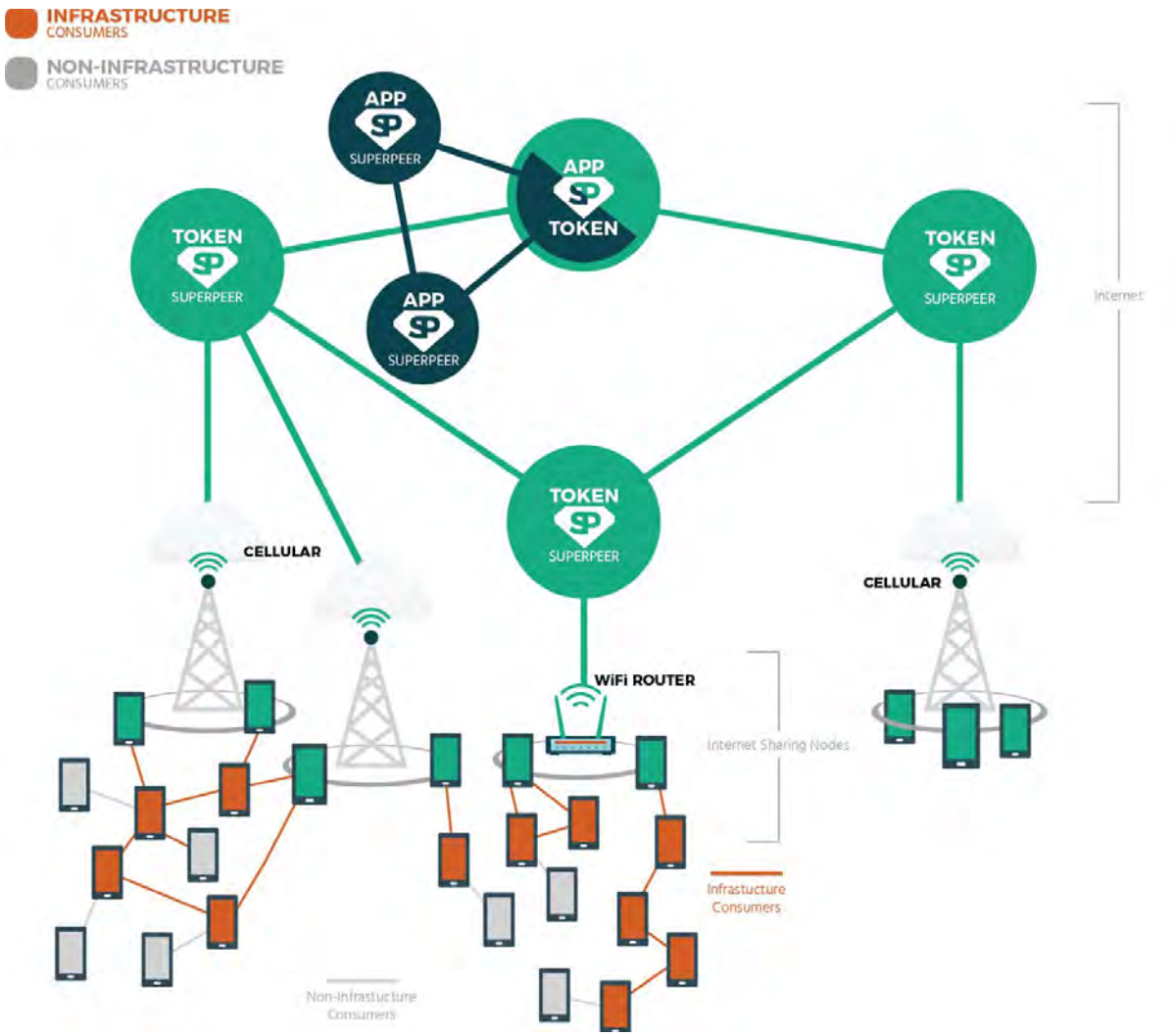


Fig. 46: *Linking distinct RightMesh networks with token SUPERPEERs*

The token SUPERPEERs themselves would essentially be running at the edges of the mesh—connected to both RightMesh and the IP Internet—with a stable, reliable, and fast Internet connection. Some of these nodes would be run by RightMesh directly and some by community partners. This model may evolve into an industry on top of our ecosystem since these nodes can earn tokens by performing a mining-like function to keep the network operating [note: no new tokens are created within this process].

At launch, these SUPERPEERs would be run on computers or on existing cloud providers spread geographically around the world. In the future, as mobile devices improve, we believe it will be possible to eliminate this centralized aspect, as much of this functionality may move directly into the Internet Sharing

Devices themselves. At present, the biggest limitation is hardware, as it is not feasible for phones to act as full Ethereum nodes. The SUPERPEER functions as a a hole-punching aid, a translator between the IP-based Internet and our mesh protocols, and an Ethereum full-node.

When the SUPERPEER recognizes that a remotely signed transaction is being passed to it, the SUPERPEER executes the transaction on its local geth instance and waits for the confirmation. It then passes the result back to the device in the network which executed the transaction. This means that any device within a RightMesh network is able to send an ERC-20 compatible token to another device, query its own token balance, and execute contracts on the Ethereum network from potentially many hops away from the Internet. At best, as far as we know, thin clients exist on mobile phones which can perform similar capabilities when the device is connected to the Internet directly. However, nothing exists that allows for cryptocurrency transactions from outside of the range of traditional IP-based Internet access.

All of the code that for micropayment channels using microRaiden and Ethereum have been open sourced (along with any contracts), so that the community can verify and improve upon the stability of the platform and to encourage the users to trust that things are operating correctly. RightMesh has also open sourced some of its own created apps to demonstrate possible implementations of the Mesh SDK: https://github.com/RightMesh. The company will explore open sourcing its core mesh technology once the network becomes hardened and the network established.

From a developer's perspective, they simply need to define the transaction they wish to make within their RightMesh application, and issue a call to our library. RightMesh will perform the transaction signing and optimize how to route the packet out of the mesh and into the Ethereum network. The full Ethereum node at the edge of the mesh is also running a Java version of our library. It uses the local remote procedure call (RPC) mechanisms to relay the transaction to a locally-running Geth client. The Geth client verifies the transaction and executes it. The result of the verification and execution will then be relayed back to the mesh node which originated the transaction. Using a similar approach, RightMesh could adapt to support other cryptocurrencies as well, such as Bitcoin.

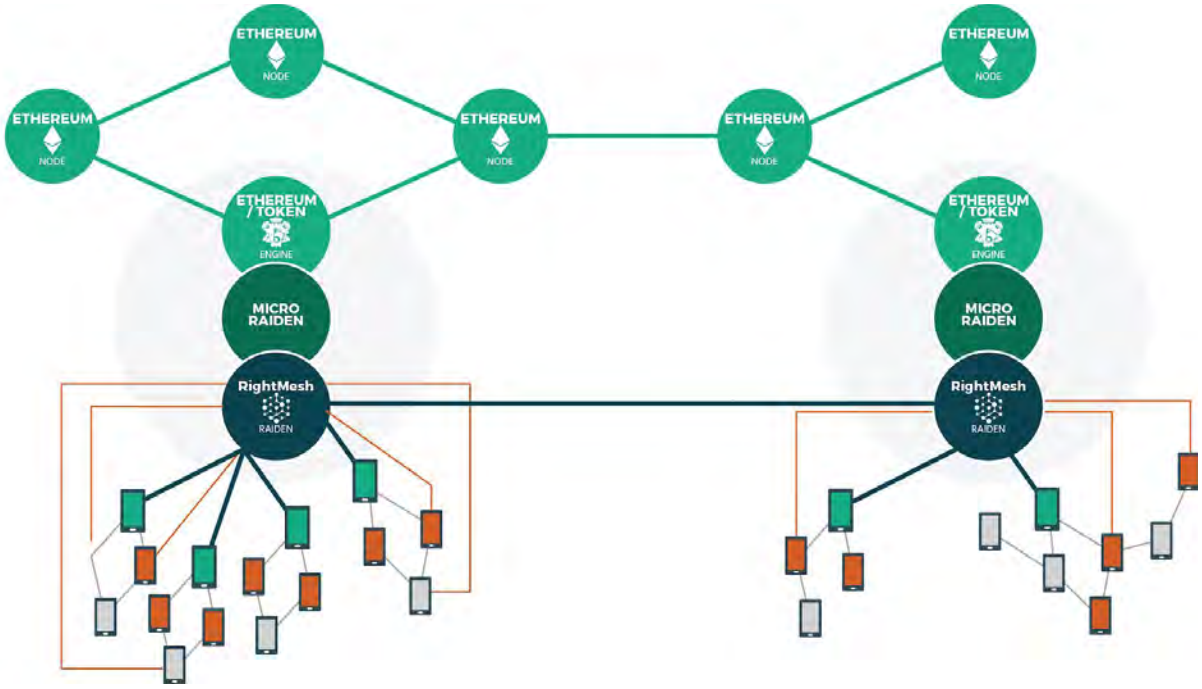


Fig. 47: *RightMesh Token Incentivization System Architecture*

Fig. 47 shows four distinct local RightMesh networks with two participating token SUPERPEERs. There could also be non-token SUPERPEERs involved - which we call "app" SUPERPEERs, however, we have left them out of this figure for simplicity. In this figure, the left SUPERPEER has two geographically separate meshes attached to it while the right SUPERPEER has two different geographically separate meshes attached to it. The SUPERPEERs may be deployed all around the world, similar to how AWS instances are deployed in different places based on geography and demand. The left Superpeer may be deployed in Canada, and have a mesh in Vancouver and a mesh in Toronto, while the right SUPERPEER may be deployed in Bangladesh and have a mesh in Dhaka and a mesh in Khulna. The green line represents a fast internet connection between the two SUPERPEERs. This is important because in the initial implementation, the data will be relayed directly between the superpeers to reach the farther meshes. In addition, the SUPERPEERs are running full Ethereum nodes. On the Ethereum network, the two token SUPERPEERs may also be peers of each other. In addition, there may be many public peers on the Ethereum network.

RightMesh Token Incentivization System Implementation

Now that the architecture has been outlined, the remainder of this section will focus on specific changes to support the functioning implementation. This includes additional roles, changes to the discovery protocol,

the data transmission protocol, channel opening and closing, and also a short discussion on the reference implementation of the token Superpeer.

Additional Roles (SELLER, BUYER, RELAY)

Some portion of the devices provide supply of resources (bandwidth, storage, processing, battery) to the network. In the case of bandwidth for sharing data, these are the Internet sharing devices or SELLERs. In Fig. 48 and Fig. 49, these are the devices connected directly to the token superpeers. Devices which aid in delivering the supply of resources to the consumers (BUYERs) are called forwarders or RELAYs. The BUYERs may be scattered throughout the mesh, and at times they may be both BUYERs and RELAYs.

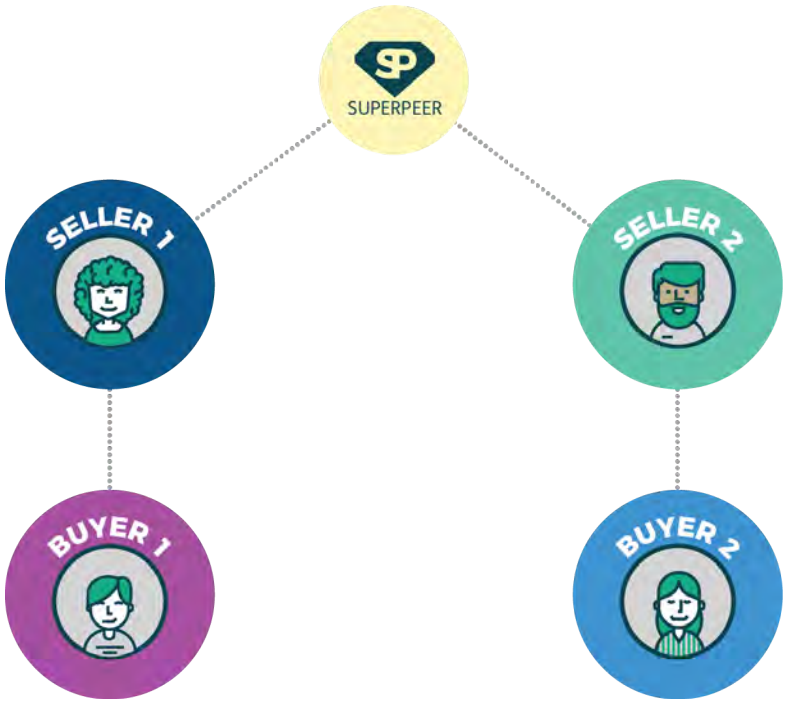


Fig. 48: *The network topology we will consider as the simplest case*

For the remainder of the discussion on RightMesh token channels, we will focus on a simple topology (Fig. 48) which shows a single SUPERPEER and two distinct mesh networks, each with one buyer and one seller. We will not consider RELAYs initially; however, they would exist between the BUYER and SELLER. All peers which are not on the SUPERPEER side of the network are called REMOTEPEERs for this discussion.

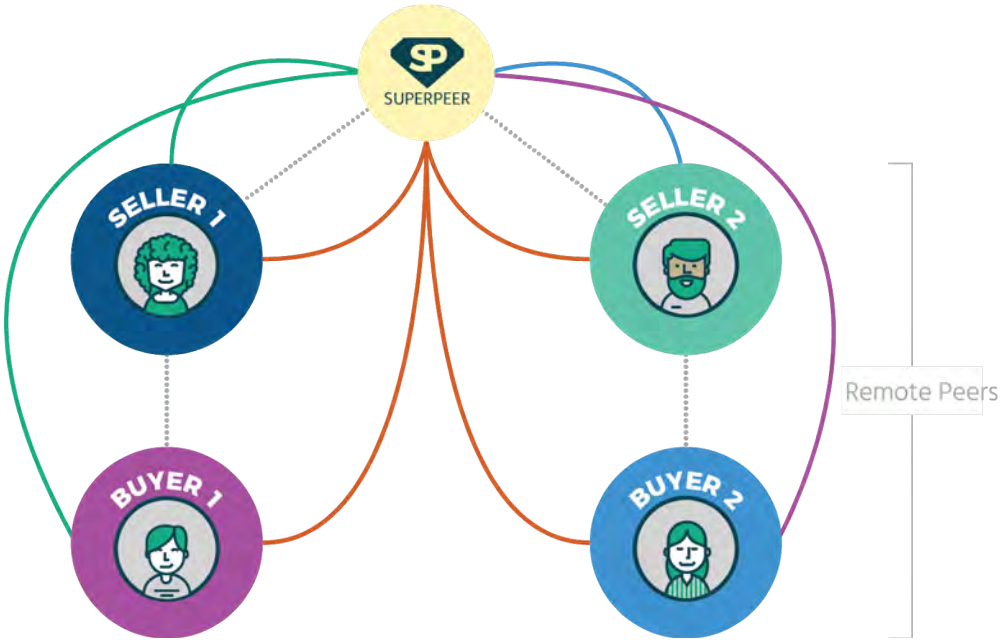


Fig. 49: *Simple BUYER / SELLER topology with payment channels for simplest case*

Incentivization is currently possible when a device wants to send traffic from one separate mesh to another through the Internet Sharing Devices via the SUPERPEERs. In order to support this, RightMesh would need to provide general purpose Internet functionality, which is on the roadmap. In this case, a PROXY role would also be required which would be a new class of SUPERPEER. SUPERPEERs would then be able to charge higher fees to provide more services. Mesh-to-mesh relaying could be a lower fee than Mesh-to-Mesh and General Purpose activity.

Changes to the Mesh Discovery Protocol

One of the biggest changes to the discovery protocol is that extra fields which provide pricing details from the Internet Sharing Devices (SELLERs) to the rest of the local mesh. This is set by users of the SELLER devices. The user simply opens the settings for the RightMesh service and sets the price. This has the effect of propagating this change to all devices in the local mesh. Similarly, potential BUYER devices can use the same settings interface to set the maximum rate they are willing to purchase data for.

Fig. 50 shows the wallet built into the RightMesh service. This lets users set the price for which they are willing to buy or sell data. This UI hooks into the discovery protocol, so when a user changes the price they are willing to sell, it updates all other devices nearby. If data packets continue to arrive before the change

has propagated, the SELLER device will be able to tell. This is because the data packets contain the balance proof, and a signature indicates how much is being paid for the data that is about to be sent. If the BUYER has not received the updated price yet, the packet will be dropped by the SELLER. By the time a re-transmit occurs, the price should be updated in the BUYER device and operations will continue as normal. In order to speed up this process, instead of dropping the packet, the SELLER could send a modified DATA_ACK packet to the BUYER indicating that the price has changed. This would trigger a retransmit of the data immediately with updated pricing attached to the data.

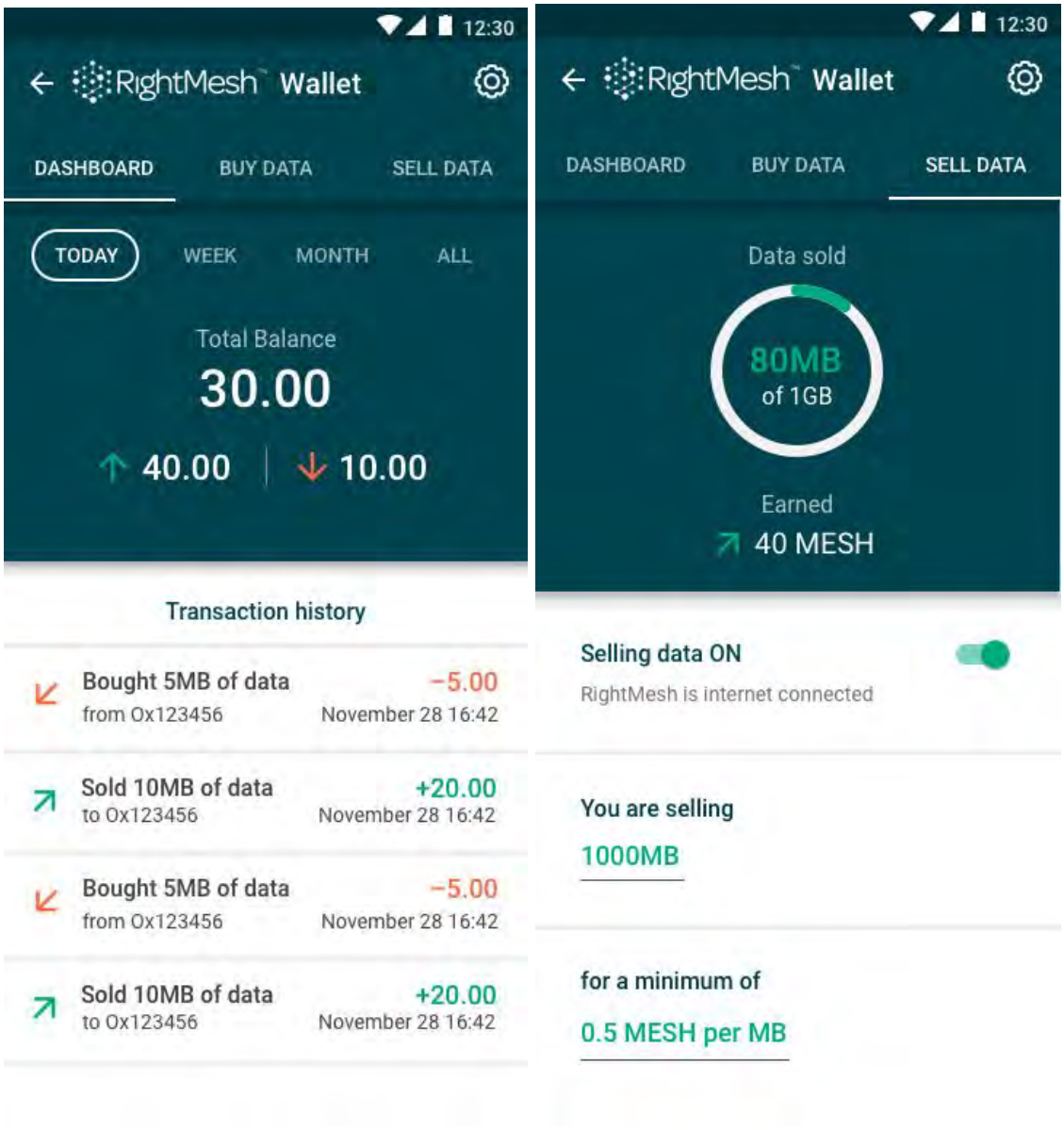


Fig. 50: *Example of the Wallet functionality built into the RightMesh service.*

Channel Opening and Closing

In order for a payment to actually occur between nodes, payment channels must be established. RightMesh makes use of the token SUPERPEERs acting as payment hubs. The reason for this is because if payment channels were established between every device pairwise in the mesh, there would be more data flowing to create and manage channels than there would be any real data. Furthermore, pairwise channels between all possible nodes would be very sensitive to changes in topology which is common in a mobile mesh network.

A new type of packet, called GET_ALL, on top of the reliable data transmission has been created to help with establishment and closing of payment channels. When a REMOTEPEER device discovers a token SUPERPEER in its local mesh for the first time, it sends out this GET_ALL packet which is relayed to the token SUPERPEER. The token SUPERPEER then queries the payment channel smart contract to determine if an outgoing channel from the SUPERPEER and REMOTEPEER exists. If one does not exist, the SUPERPEER creates one. This part requires no remote transactions from the REMOTEPEER side, just the MeshID. It also checks if an incoming channel exists from the REMOTEPEER to the SUPERPEER.

In the response, the SUPERPEER returns whether the channel exists from the REMOTEPEER to the SUPERPEER, the RightMesh Token balance of both of the channels and the Ethereum balance of the MeshID. The REMOTEPEER will examine the response, and if the channel does not exist from the REMOTEPEER to the SUPERPEER, the REMOTEPEER will prepare a follow-up packet with two signed transactions: one approving funding of a new channel, and one for creation of the channel.

The first transaction is to approve the payment channel smart contract to transfer a number of tokens from remote peer's account. This will be the deposit amount. The function called in the first transaction is defined in ERC-20 RightMesh token smart contract. The second transaction is to create a payment channel. The function called in the second transaction is defined in payment channel smart contract (based off of micro Raiden).

Generally speaking, after a unidirectional payment channel is created, either payer (token sender) or payee (token receiver) can close the payment channel as long as one has both the balance-proof and closing-hash signatures created with a same balance. After closing the channel, the balance amount of token will be sent to the payee's account. The rest of the tokens not yet spent by the payer will be reimbursed to the payer.

Changes to the Data Transmission Protocol for Data Accounting

The data transmission protocol depends on a Raiden micropayment channel being established from the BUYER device and the token SUPERPEER. Similarly, for a SELLER we assume a channel has been established from the token SUPERPEER to the SELLER. As part of the packetization and routing process, the RightMesh library is able to compute the price of each packet from BUYER to the SUPERPEER based on the cost of the route set by the SELLER.

The balance-proof is a signature signed/created by the payer. The closing-hash is signed/created by the payee. So, to enable the above the functionality, we include balance-proof and/or closing-hash in the packet header of DATA and DATA_ACK packet.

Consider again the topology outlined in Fig. 48 and Fig. 49, the simplest case for data transmission and tokens. Buyer1 and Buyer2 wish to communicate over a long distance and they do not have cellular network or WiFi. As such, they would like to communicate over the Internet by using RightMesh service. Each remote peer is a buyer buying Internet data from a seller (the gateway peers who have Internet access) on each side. Without loss of generality, we assume buyer1 acquires data from seller1 and buyer2 acquires data from seller2. Both seller1 and seller2 can access a Superpeer in the middle.

Unidirectional payments are created as follows:

- From buyer1 to SUPERPEER
- From SUPERPEER to seller1
- From buyer2 to Superpeer
- From SUPERPEER to seller2

Now, assume buyer1 is sending an Internet data packet to buyer2. The library will first check if the aforementioned payment channels are ready to use. If not, the channels have to be created first.

Then, as shown in Fig. 51, according to the data selling price of seller1 listed in the routing table (e.g., 2 tokens per byte), buyer1 will sign the first balance-proof signature (BPS) and add the signature in the packet header (purple signature in Fig. 51). Buyer1 will save the balance and BPS in a table at its memory. This BPS is used to pay the Superpeer. When seller1 receives the packet from buyer1, since it knows that it is a seller and get paid by Superpeer, so seller1 will add a closing-hash signature (CHS), the left yellow signature in Fig. 51, to

acknowledge the previous BPS received from Superpeer. As we are transmitting the first packet, and the Superpeer has not paid seller1 before, the CHS is with zero balance. The target of the CHS, signed by seller1, is the Superpeer.

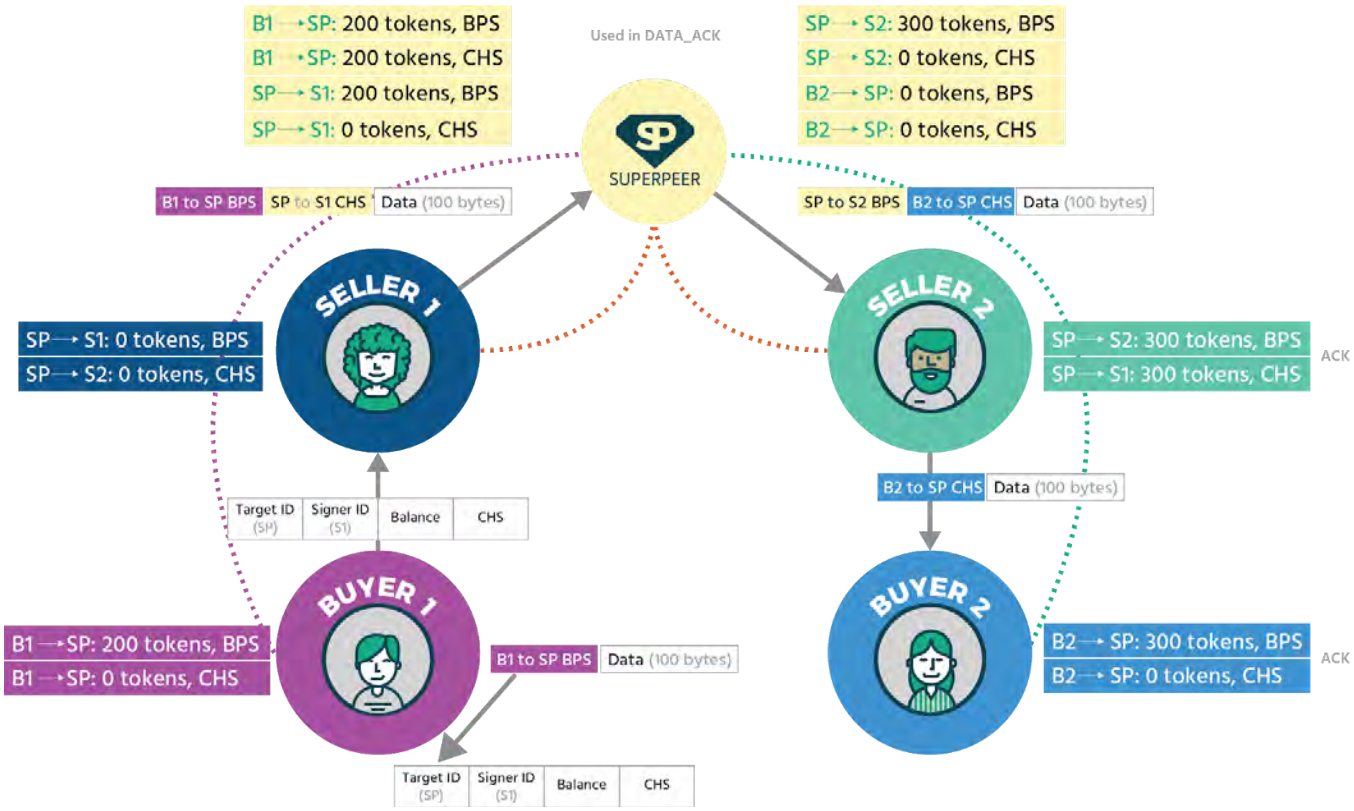


***Fig. 51**: Balance proof signatures being attached to DATA and DATA_ACK packets*

In Fig. 51, when the Superpeer receives the DATA packet, it finds out first if there are BPS from buyer1 and the CHS from seller1 sending to it. The Superpeer takes out both signatures from the packet header and saves/updates corresponding signatures in the table. Whenever a BPS is received by the payee, the CHS will be created by the payee automatically. In our situation, the Superpeer receives the BPS from buyer1, so a CHS is created/signed by the Superpeer. The CHS will not send back to buyer1 immediately. It will be added in the packet header of DATA_ACK when the acknowledge is sent from buyer2 to buyer1. We are going to revisit this part later.

The Superpeer is responsible to forward the packet to its destination (buyer2). Note that the BPS and CHS from buyer1 and seller1 have been removed from the packet header. Now, the Superpeer needs to include a

new BPS to pay seller2 (the right yellow signature in Fig. 51) and a new CHS (blue signature in Fig. 51) to acknowledge the payment sent by buyer2 along with the previous packets. Since we are delivering the first DATA, the CHS to buyer2 has a balance equal to zero. The balance in the BPS from Superpeer to seller2 is calculated according to the data selling price of seller2 given by the routing table (e.g., 3 tokens per byte). Both these signatures will also be saved in the table of the Superpeer.

In Fig. 51, when the DATA packet reached seller2, the seller2 finds out if there is a BPS sending to it. Seller2 takes out the BPS. Seller2 creates/updates the CHS with respect to the Superpeer, but it will not send the CHS directly. The CHS will be contained in the header of DATA_ACK (we are going to revisit this later). Seller2 continually forwards the DATA packet to buyer2. Note that CHS is signed by the Superpeer to acknowledge the payment from buyer2 to Superpeer is still in the packet header. When the DATA packet eventually reaches buyer2, buyer2 takes out the CHS (which has zero-balance since buyer2 has never paid Superpeer before) and updates it in its table.

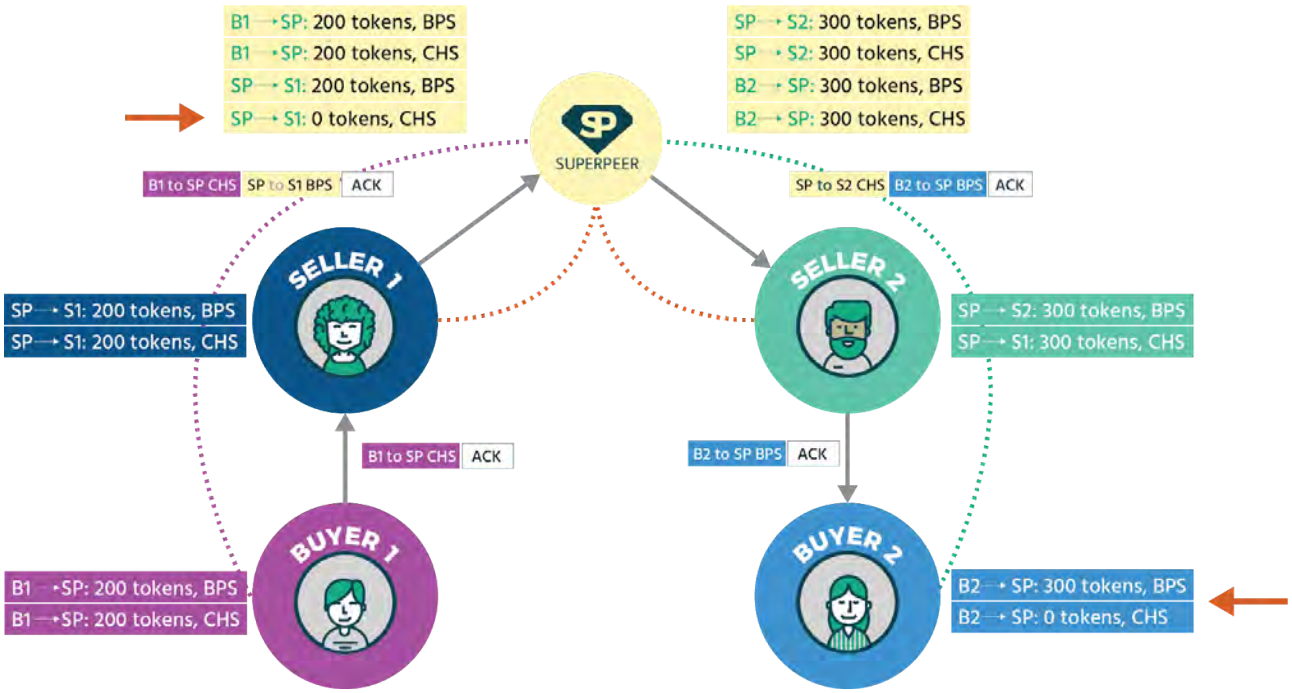


Fig. 52: *Balance proof signatures being attached to DATA and DATA_ACK packets*

According to the size of DATA packet received and the data selling price of seller2 from routing table, buyer2 creates BPS to pay for Superpeer. As shown in Fig. 52, the BPS (blue signature in Fig. 52) will be

included in the header of DATA_ACK sending back to buyer1. The created BPS for the payment channel from buyer2 to Superpeer will be saved in the table at buyer2.

When DATA_ACK reaches seller2, the seller2 will first add its CHS (created upon the DATA reception from Superpeer previously, the yellow signature at right of Fig. 52) in the DATA_ACK header, then forward the DATA_ACK to the Superpeer.

In Fig. 52, the Superpeer takes out the BPS sent by buyer2 and the CHS sent by seller1. Both signatures are logged or used to update the existing entries. The Superpeer also creates a CHS to acknowledge the received BPS for the payment channel from buyer2 to Superpeer and keeps that in its memory. These two signatures are removed and replaced by two new signatures: one is the BPS to pay for seller1 (the left yellow signature, created upon the DATA reception from seller1 previously) ; one is the CHS to acknowledge the BPS received from buyer1 (the purple signature, Superpeer had created the closing-hash when it received the DATA packet). The DATA_ACK is then forwarded to seller1.

Seller1 receives DATA_ACK and finds out there is a BPS sending to it. It takes the BPS out (the left yellow signature in Fig. 52) and saves it in the memory for the payment channel from Superpeer to seller1. Seller1 creates a CHS to acknowledge the BPS, and holds it in the memory for now. Seller1 then forwards the DATA_ACK towards buyer1.

Buyer1 receives DATA_ACK and knows that DATA packet has been successfully sent. Buyer1 finds that there is a CHS (purple signature in Fig. 52) sent from Superpeer which acknowledges the BPS sent along with the previous DATA. The CHS is logged and used to update the existing one in its memory.

It is worth mentioning that:

1. The BPS from Superpeer to seller1 was received by seller1 and a corresponding CHS was created, but the CHS had not yet sent it back to the Superpeer.
2. The BPS from buyer2 to Superpeer was received by the Superpeer and a corresponding CHS was created, but the CHS has not yet sent it back to buyer2.

These two signatures will be added in the packet header of the next DATA packet from buyer1 to buyer2.

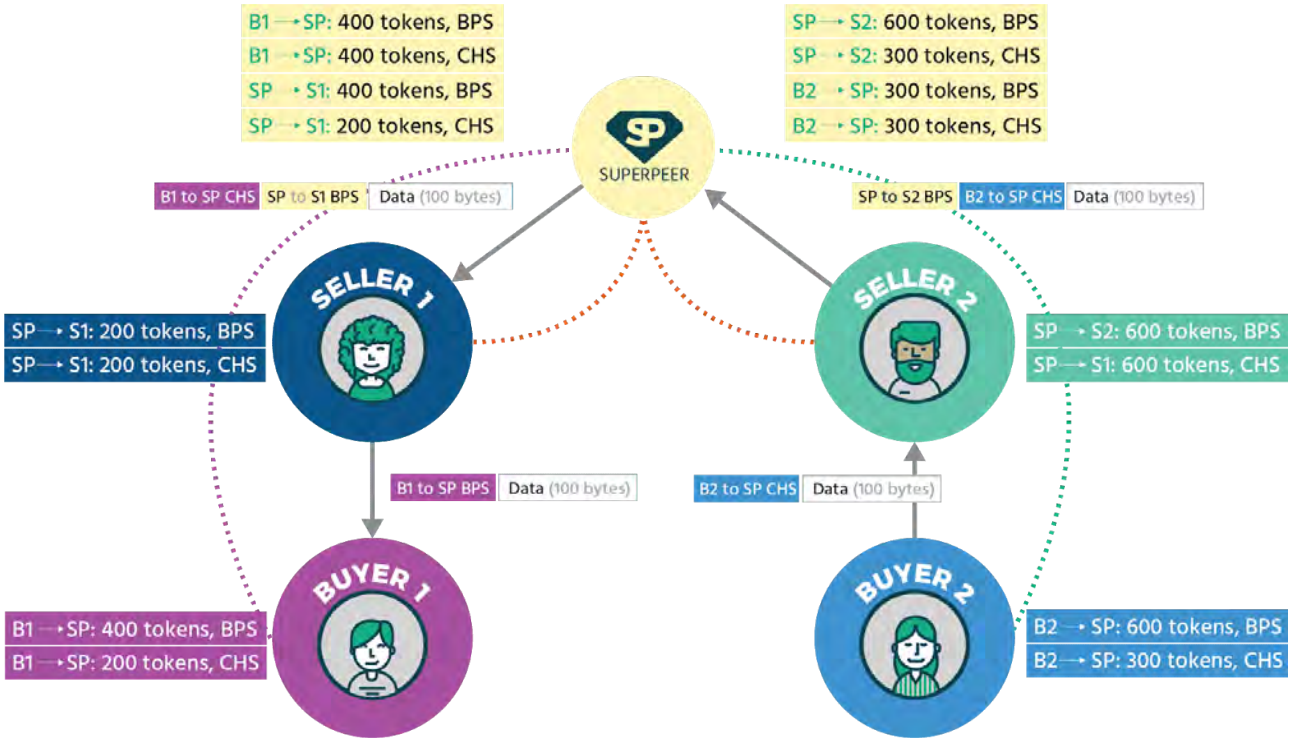


***Fig. 53**: Balance proof signatures being attached to DATA and DATA_ACK packets*

There are similar routines for the next DATA packet and DATA_ACK, shown in Fig. 53 and Fig. 54. For each counterpart of each payment channel, the BPS and CHS are saved/updated when DATA and DATA_ACK packets are received. One can begin closing its payment channel by calling the close channel function in smart contract with both BPS and CHS.

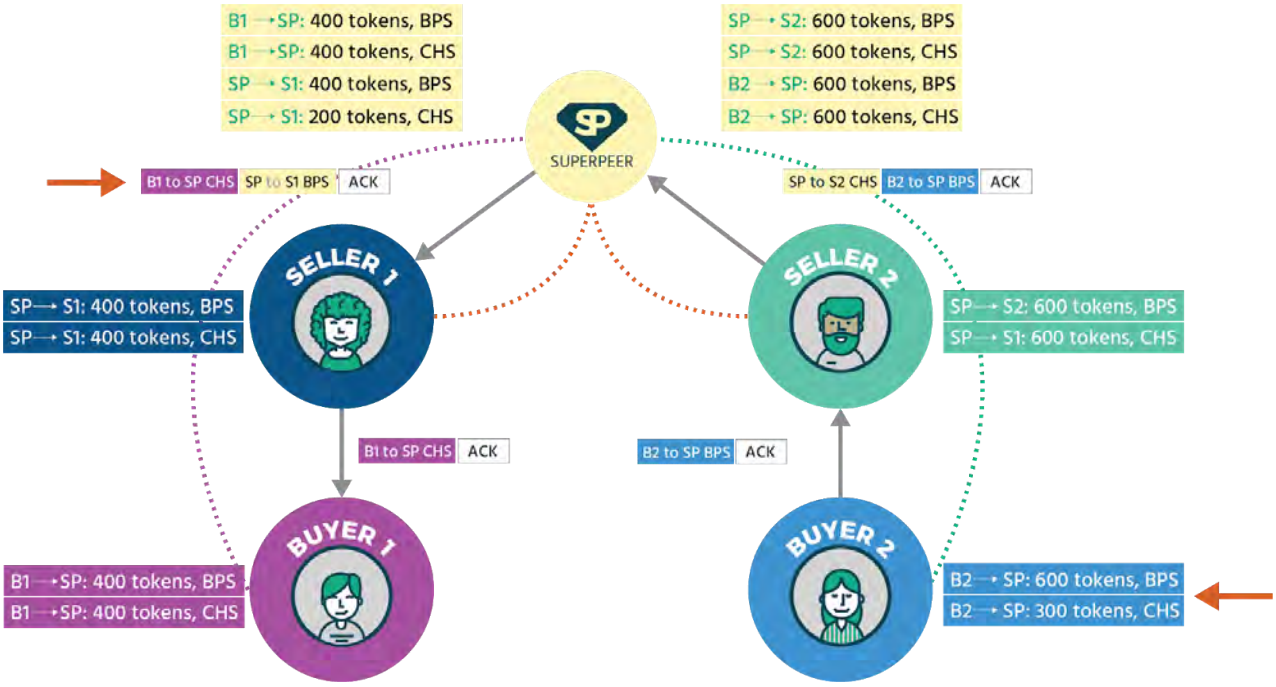


***Fig. 54**: Balance proof signatures being attached to DATA and DATA_ACK packets*

Token Superpeer Reference Implementation

A Token Superpeer reference implementation has been provided, and it is now available on Github. Currently it operates on the assumption that the Superpeer will continually have enough RightMesh tokens to fund the creation of more channels. If the Superpeer's account runs low on tokens, it would be necessary to take tokens out of the established channels which are not earning any funds and move them into channels which have higher likelihood to continue moving tokens around. Currently, we have setup the reference implementation such that a person using a console can close channels. This would free up funds to continue operating; however, it is our intent to automate this process. As such, we believe it is likely that a community of SUPERPEER developers and operators may emerge and compete with each other on their funding of token SUPERPEERs as well as opening and closing channel strategy.

6. Platform / Ecosystem

The RightMesh developer ecosystem encompasses all of the tools, resources, and community available to developers to build RightMesh apps. The ecosystem also encompases the users of the RightMesh apps.

Furthermore, the ecosystem includes parties operating key pieces of the RightMesh network: the people acting as SELLERs, SUPERPEERs, and RELAYs. Finally, the ecosystem contains partnerships with people building out particular components of the RightMesh architecture.

The place where developers should start is within the developers' portal. This is the place where developers can sign up for an account and obtain app keys. App keys will help the RightMesh team map bug reports, crashes, performance issues, and gather feedback and give support to the teams working on the RightMesh apps. Once a developer has signed up for an account, they are able to access the Java API documentation, as well as a reference section which describes some of the key pieces to building a RightMesh app.

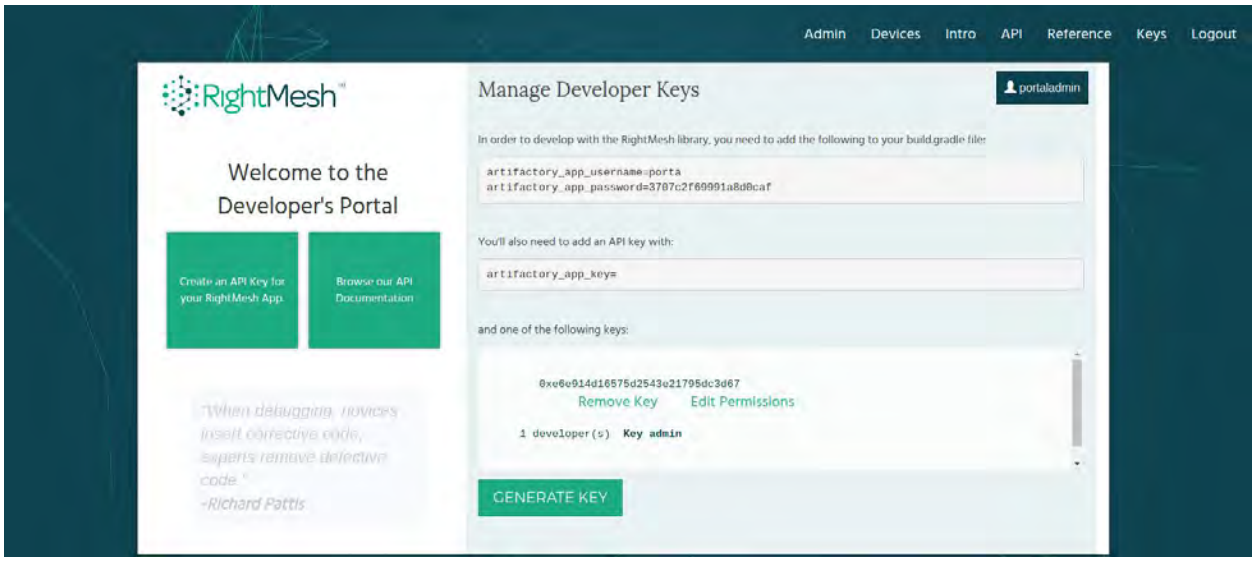


Fig. 55: *RightMesh Developers Portal*

We have also built a growing repository of sample RightMesh apps on GitHub, including the usual "Hello Mesh" app, but also a "ping" type of app called "Reflect", a an app which shows of how data routing follows a unicast path called "Ripple", our reference implementation of a "token Superpeer" and a messaging app called "MeshIM". Our Bangladesh team has been developing an emergency app called "Flare" which is not yet open source. MeshIM and Flare are the first apps which are moving towards becoming commercial apps, while the others are mostly demonstration apps. This is just a small snapshot of what is possible within RightMesh and we are working with key partners to build out further commercial and real-life applications as well as innovating on applications that take advantage of the unique properties and capabilities that RightMesh provides.

Furthermore, the involvement of the Superpeer in RightMesh opens the door for many interesting applications within the ecosystem. App developers could use it as the translation point between mesh apps and non-mesh portions. Services to push content out to users could be created that are much more efficient to the partners operating the services. For example, when someone wants to push out a 200MB video advertisement to 1M people. Unless they are using IP multicasting, a single video may be sent 1M times x 200MB, which with simple math equates to 200TB of data. Integrating this "push" outwards with a RightMesh Superpeer, the push could occur more strategically (perhaps once per mesh) dramatically lowering the amount of data required. The bandwidth costs of the push is significantly lowered, and the efficiency of the Internet links are significantly improved.

Similarly in the opposite direction, similar gains can be made by collecting up sensor readings, aggregating the results at local superpeers and then pushing them out onto the Internet strategically.

The last part of the RightMesh ecosystem is the opportunity to interoperate with many complimentary distributed systems. There are several mesh initiatives that are more infrastructure and hardware focused which are complementary to RightMesh, and even other mesh initiatives on mobile phones which may be able to interoperate with RightMesh. The goal of all of these projects should be to free people from the centralized infrastructure and corporations controlling it, and as such we should be strongly motivated to work together.

While RightMesh users are pseudo-anonymous when they are acting as buyers and relays, they are less so when they acting as sellers, where they may have public IP addresses. Partnering with systems such as ORCHID Labs (Orchid Protocol) at the edges of the mesh would allow for devices to become anonymous in mesh even at the edges.

When it comes to incentivizing resources, RightMesh currently focuses on incentives for data; however, interoperability with decenctralized storage systems (e.g., Filecoin or Storj) may help with incentivizing on-device caching and storage. Similarly, individuals can be incentivized for on-device processing (Golem) or on-device data/sensor information (SingularityNET).

7. Future Technical Roadmap

While there are details and hints at our roadmap scattered through this document, this section collects the most important milestones and future roadmap elements to come in one spot, so that readers can understand clearly what has been built, what will be built, and what needs to be fleshed out.

Users are encouraged to read the full product roadmap in the RightMesh White Paper for additional details on our roadmap approach and lifecycle stages.

What Works Today:

As of March, 2018, RightMesh has a basic mesh networking platform developed for Android devices. The platform as it stands now is a library that supports multihop connectivity between many devices (we have had up to 30 so far on a single mesh) and can cover long distances (we have achieved about 1000 feet with only 5 devices. We will need to do further experimentation to cover longer distances). We have done initial pilot projects and tests in Rigolet, Labrador in Northern Canada, as well as tests with our team in Bangladesh, and in Vancouver, Canada.

There are several sample apps available on our public GitHub repository: https://github.com/RightMesh including a “hello mesh” app which gives an introduction to developers, a colour changing demo that illustrates how our library forms routes compared to the broadcasting libraries, a “ping test” type of app which is good for coverage testing, and soon there will be a simple “hello Java” app which shows the same type of code running on a something like a personal computer, Raspberry Pi, or other device running Java.

The mesh portion of the library is becoming quite mature. The connectivity aspect supports Wi-Fi, Wi-Fi Direct, and Bluetooth and has two provisional patents covering it. A third patent has also been filed. It is partially autonomous right now, in that once the user selects which technologies to enable and which role they wish to be in (hotspot, switching, or client) the network will self form. We are working on what we call “fully autonomous” mode where the library can figure out the best mixture of these roles and technologies to enable.

We have put quite a lot of time into a Developer's Portal, so our library is easy to program with, and well documented. This includes Javadocs, a step-by-step *Getting Started Guide*, and information about what to include in Gradle. In the future, we intend to add more tools to support developers such as bug reporting and collection from the RightMesh library automatically into the developer portal. We will also support deploying test cases and performance stress testing directly from the developer portal, so developers can determine if there app is causing a problem or if the mesh protocol is not performing correctly.

More recently, we have made great progress on the token incentivization. We can now automatically open micropayment channels between devices when they first obtain an Internet connection, attach tokens to data transfers, and close the token channel which effectively enables payments from one device to another for bandwidth. This is operational on the Kovan testnet.

What is Next to Come:

The next major milestone on the mesh side is real performance analysis. While we don't have official performance numbers we can stand by yet, we have small scale evidence over a small number of hops that we can achieve high performance (on the order of Mbps). It is our intent to obtain future performance numbers using a scientifically rigorous process., As we go farther down this road, we will release further apps that allow for throughput and delay measurement testing, so the community can try out the mesh and perform their own tests to see where and how it works best.

Along with the performance analysis, it will be important to get a clear idea on how the network performance changes as the network grows. Where are the bottlenecks, how does performance degrade over hops, and how many Internet sharing devices can one Superpeer support? How many consumers can one internet sharing device support? Also, with <x> devices consuming data, how quickly will <y> data be consumed? After we answer some of these questions, there will be lots of opportunities to improve the performance as we will learn a significant amount about where the network is weak, while helping us generate ideas on how to improve.

One of the biggest challenges for us on the network side is automated testing of the library. Given that much of the operation of the library depends on complex connection topologies between groups of phones, it is difficult to simulate effectively. There is some portion of the library that we have applied unit testing and limited offline testing to; however, some of it requires real device testing as there are aspects that need

to be tested that are specific to particular Android versions, the orientation of the phones near to each other, and the order in which the devices discover each other. We would like to support phones from Android 4.x to present; however, with the wide range of capabilities, the way Android handles permissions, and other differences between devices, this means there is a huge scaling problem to automating the whole process since the number of testing possibilities grows exponentially as the mesh size grows. We are looking at ways to automate as a much of this as possible so future builds are stable across a wide range of devices.

There is still more work to be done the incentivization side. Our current proof of concept supports a simple topology; however, we would like to extend this to multiple superpeers, and provide tokens to relay devices in between. We are almost at the state where the relay devices may be provided tokens, but are still a few weeks away from supporting multiple superpeers. We also would like to put more concentrated thought into the economics and incentive structures to ensure that tokens move around the system in a stable manner. Once the basic data sharing incentive structure is in place and well understood, the next step will be apps for ad and app distribution, “data mule” incentives, storage/caching, processing, and more.

We are also rapidly growing our team in Canada, and are on the lookout for more talent. Whereas others are building walls, do note that Canada has a new two-week processing program for skilled workers under a new initiative to invite the world. We do not discriminate based on location, nationality, religion, or sexual orientation, and are consistently recognized as one of the Best Workplaces in British Columbia, including winning the award in two straight year from the BC Tech Association as the best tech company in BC that balances, “Work, Life, and Play”. So if you have experience (either academic or professional), passion, and a commitment to doing things right, we would appreciate hearing from you.

We welcome feedback via Git, Telegram, and more methods identified below.

Additional Resources & Links

- RightMesh White Paper: https://www.rightmesh.com/whitepaper
- Website: https://www.rightmesh.io
- Developer Portal: https://www.rightmesh.io/developers/
- Corporate Blog: https://www.rightmesh.io/news/
- Twitter: https://twitter.com/Right_Mesh
- Telegram: https://telegram.me/RightMesh_Official
- GitHub: https://github.com/rightmesh
- Careers: https://www.left.io/careers