Wi-Fi® mesh networks: Discover new wireless paths

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Abstract

With recent advances of in Wi-Fi® technology, specifically in its ease of implementation and ability to meet the requirements of a majority of connectivity use cases; it has become one of the dominant wireless solutions. The continuous progress in this wireless technology has propelled its successful penetration in a variety of applications. So, it also became a highly requested connectivity solution in large-scale use cases for which it was not originally developed.

The wireless networks became more complicated with sophisticated structures in which the regular access point (AP)-based topology appeared to be a less efficient solution. The requirement of constructing such networks in which more than one hop will be used, has enforced the IEEE organization to compose the IEEE Std 802.11s-2011 mesh networking amendment on top of the IEEE Std 802.11™ specifications document. This amendment became an integral part of the IEEE Std 802.11-2012.

In this paper, we will discuss wireless mesh networking from the top down. We will cover its main concepts and advantages and show a variety of possible wireless mesh applications along with a general deployment consideration. We will then deep-dive into the core features composing its implementation and, finally, show what improvements Texas Instruments (TI) has released based on the Linux® open-source 802.11s implementation.

Introduction

It's possible now to have a fiber optic cable connected directly to an expensive, high-end router, but it will just make it more frustrating when the Wi-Fi signal is not good enough to hold a solid connection to your device. Wi-Fi extenders and repeaters can be used to extend range, but due to the nature of the wireless medium, in many cases such installation will fail to provide the desired bandwidth.

Furthermore, it is also required to pre-define roles and responsibilities for each device. The access point will have to be placed in locations that will permit providing service to all of its clients and this fixed positioning has to be maintained to preserve the network connectivity.

Wi-Fi mesh networks have disrupted these two basic assumptions. Every mesh node is equivalent to the others, which makes the network independent with a self-forming capability. After an initial setup, the device can be located wherever it's needed; it can act as an endpoint, a range extender and even a gateway to an external network. A mesh network can rearrange itself using a self-healing mechanism, to support cases in which some nodes have changed their position or have been turned off.

With such capabilities, new use cases and topologies for Wi-Fi technology usage have been opened. These use cases range from a closed loop system that supports machine-to-machine (M2M) topology, through a home automation deployment and up to a smart grid use case that can be constructed using a huge number of hops and nodes.

The mesh-capable device might have only basic IEEE 802.11s features and be able to construct a mesh network or be loaded with more sophisticated features like precise synchronization between devices, a concurrent operation of the mesh and other Wi-Fi roles, a dynamic transition between mesh network and AP-based network and so on.

However, mesh networks have a major consideration on the bandwidth they can handle. As the best path to transfer data from one point to the other can constantly change, it is crucial to determine the best route in a dynamic, reliable way and as quickly as possible. Although, there are many routing algorithms out there, it's not a trivial task to fine tune the best path selection algorithms to achieve an optimal Wi-Fi behavior.

Mesh network use cases

General capabilities

A mesh network can be used for a wide variety of scenarios, outside of the basic capability to transfer data over a distributed deployment. There are several advanced capabilities that might be required from mesh devices in order to support most of the use cases. Examples of such capabilities can be:

- Ethernet bridged mesh station (STA) is a simple and robust way of creating a mesh network leveraging its benefits without overloading any existing infrastructure and even taking advantage of a separated channel. When reliable and high-performance data transfer is required, this should be the selected configuration. A great example of this is wireless audio speakers where the music is played across multiple devices, sometimes out of range of the home AP.
- Concurrent operation of mesh STA and AP role can be used to allow connection of legacy station devices to a mesh network. This can be very useful in M2M scenarios where the devices are all connected to each other through the mesh network but can be controlled and accessed through STA devices handled by the operators.
- Concurrent operation of mesh STA and STA role can be used to connect the mesh network to a standard AP infrastructure for Internet access; it is a huge advantage for home automation devices. In such a configuration, all of the appliances will connect to each other seamlessly and will form an independent network which can be used to pass information between them while reducing the dependency on the home AP. A single device connected to the home AP will provide Internet access when needed.
- Dynamic transition between STA and mesh STA link establishment. In this type of configuration there will be just a single active link the majority of the time, as opposed to the case where both links are kept concurrently. The transition will be based on the device's needs. If there is a good link quality with the AP, the STA link will be kept, allowing the use of the legacy power-save schemes. Once the link with the AP is degraded, the device will use the mesh STA link for improving its performance.
- An extended feature is precise synchronization between mesh devices. For STA devices this is a trivial and a required capability, by the IEEE 802.11 specification, to allow AP beacon tracking, power-save-mode operation and more. For mesh STA, this is not mandatory but it can be very helpful when a master clock is required to align all of the devices. Such a

feature can be used when synchronized music is played between speakers in the same room.

The above advanced capabilities have two common key advantages which translate into the main mesh use cases. They will be listed in the following sections.

Range extension use case

One of the major benefits of mesh deployment is the possibility to pass data between two devices that are not in range of each other. This benefit is created by taking advantage of the connection to the mesh STA devices in between. Devices can be connected in a row, one after the other, forming a chain of nodes (somewhat like a chain of city street lights). Since each added hop has an impact on the throughput and the latency of the transferred data, the number of links in such a chain and the location of the external network connection should be adjusted to meet the expected network performance.

A classic "chain" example can be city lights, connected to one or more external network APs, allowing wireless data transfer, status reports and remote control using standard Internet protocol (IP) infrastructure.

Another common deployment example can be the wireless speakers scenario where there is one speaker connected to an Internet music streaming service and providing that connection to all other

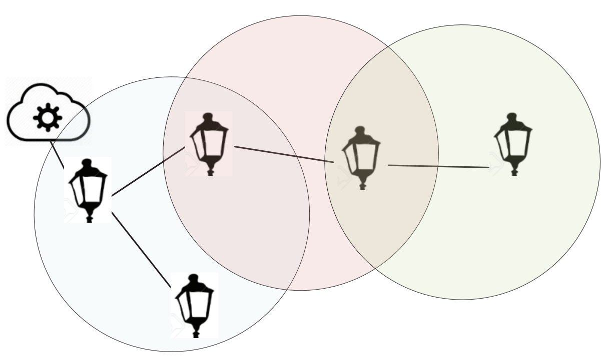

Figure 1: Use case. Range extension

speakers in that network. A mesh network can easily double the range of the Internet access and enable dynamic positioning of speakers around the house.

AP offloading use case

The demand for wireless bandwidth within a specific network is constantly increasing; more and more mobile devices are streaming video and audio content with high-quality requirements. Using a smart mesh deployment can actually offload some of the load from the legacy AP device by enabling a direct data transfer between the devices.

One of the most common examples is the wireless audio speakers scenario.

Today, many audio services can support a multi-speaker streaming playback. The audio source can be an Internet music streaming service, such as Spotify®, Pandora®, TuneIn, etc., but also local content played through Digital Living Network Alliance (DLNA) services. In any of these cases one of the devices is selected to be the "master" of the network and it is the one supplying the content to the rest of the speakers. With the legacy AP-based topology, all the information has to go through the AP to get to the other devices, as demonstrated in Figure 2 below.

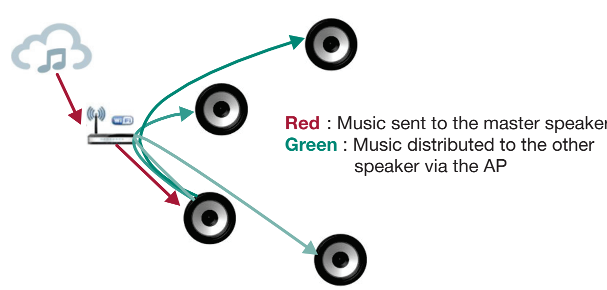

Figure 2: AP standard usage

Using the mesh network can significantly reduce the load on the AP and help utilize the air medium in higher efficiency as the speakers can transfer data directly from one to the other, as shown in Figure 3.

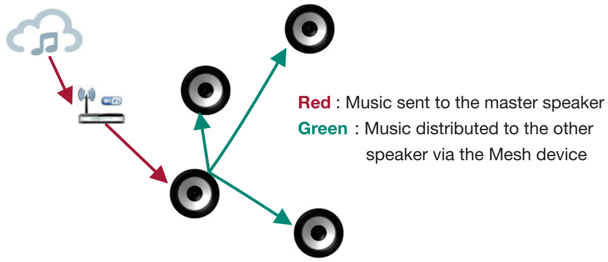

Figure 3: Use case. AP offloading

Wi-Fi mesh key features

Homogenous

Wireless mesh networks inherit capabilities from legacy AP/STA modes. Each mesh device acts as an autonomous basic service set (BSS) which is reflected in the beacons' transmission, connection handling and so on. There are no pre-configured roles to the nodes, which makes the network highly flexible and simplifies the deployment.

Self-forming

The wireless local area network (WLAN) mesh is defined as a self-forming network. The detection of other mesh devices is done by listening on a selected channel for the presence of other devices with mesh dedicated information elements (IEs) in its beacons. A suitable mesh device is one that has the same network name and uses the same security protocol. Once the suitable network is detected, a connection will be automatically initiated. The connection can be open or closed (secured) using a pre-shared key.

Dynamic path selection

One of the key concepts of a distributed network is redundancy of links in the system. This redundancy allows better resilience to node failures and allows multiple options to reach from one point to the other. Together, it imposes the challenge of selecting the best path to the desired destination.

Process description

A mesh station uses a built-in algorithm to compute a path cost, or metric. For each destination, it will be required to calculate the optimal path with the lowest link cost/metric. This is done by incorporating the hop count, signal quality, data rate and more.

The path selection process is invoked periodically, even if the mesh network is constructed as a stationary network. This is required since the air conditions might change, a device might change its position or disappear and the connection quality between devices that currently construct the best path might become worse (see Figure 4).

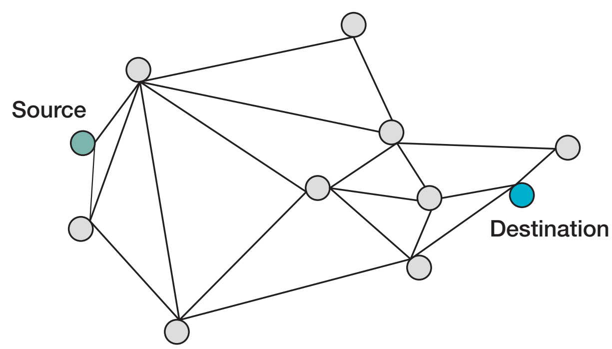

Figure 4: Only one optimal path between source and destination

The path selection algorithm selected by the IEEE to be incorporated into the specification is hybrid wireless mesh protocol (HWMP). It is divided into two main modes: “on-demand” and “proactive”, to meet the needs of different mesh network topologies and use cases.

"Proactive" mode

In this mode, once one or more devices are defined as a root mesh device through a "root announcement" frame, all the other mesh devices will start to form a path towards that node. The path selection process will be periodically invoked even when there is no data to be sent. Due to the large amount of packets continuously transmitted in this mode, it can impact utilization of networks with a high number of nodes and thus it's not recommended. Figure 5 shows the process:

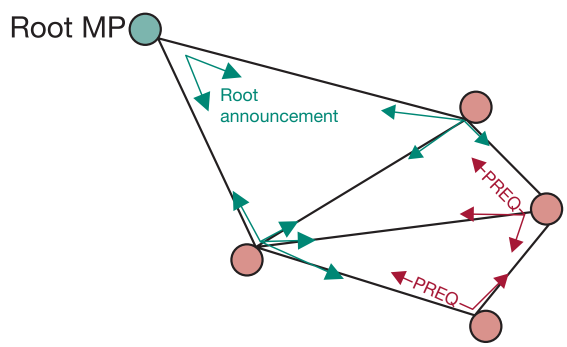

Figure 5: Root announcements distributed, causing PREQ to be sent

"On-demand" mode

The "on-demand" path selection mode is the default operation mode in the 802.11s open-source solution since it meets the needs of most of the scenarios and topologies. Also, it improves power consumption and network utilization since it will be triggered only when data is required to be sent:

- Source have data to send.
- Broadcast path request (PREQ) is sent from the source.
- Broadcast PREQ is propagated through the network nodes.
- Destination receives all the PREQ frames, and replies with a unicast path response (PREP) to the device constructing the best path to the source.
- PREP is forwarded by intermediate nodes until it reaches the source.

What might be counterintuitive is that the responsibility for determining the best path is made by the destination mesh STA and not by the originator, while the other nodes along the best path are used for passing the PREP frame from the destination toward the data source.

Figure 6 shows the process:

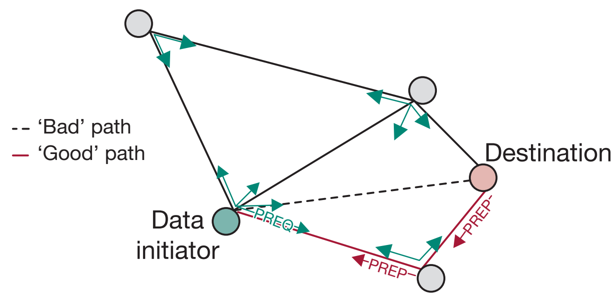

Figure 6: PREQ frames are distributed over the network reaching to the destination. The destination replies using the best path.

Intermediate nodes that pass the PREP will also capture the path cost to adjacent nodes, this is valuable to allow sharing the metric information and reduce the packet distribution. On the other hand it can cause these nodes to capture the non-optimal path and result in a performance impact.

Self-healing

The self-healing mechanism is responsible for detecting mesh devices gracefully leaving the network or an abrupt disappearance and takes an immediate action for its fixing.

In both cases, once identified, the data source will have to construct a path toward the destination. The time for the whole process has to be quick to prevent data loss and high latency. A good response time is considered within the range of 0.5–2 sec.

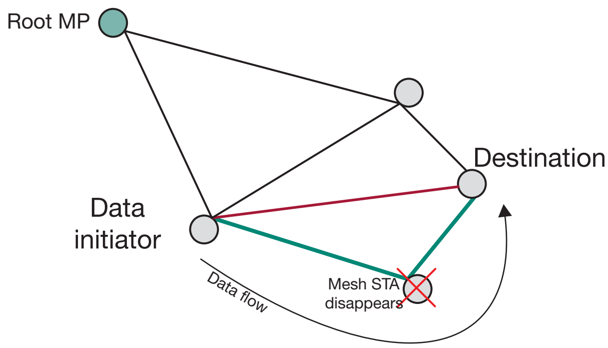

Figure 7: Mesh network where mesh device disappears

Possible issues in mesh networking

Path metric

The air metric calculation described in the specification is based on the effective transmission rate and the packet error rate. In many cases, mesh devices don't have or have a non-updated rate's information. As the result, it will not reflect the real current state and a wrong path will be selected. In fact, in any case where the data initiator has a unidirectional data sent, like User Datagram Protocol (UDP), intermediate nodes will not have any reliable information on the link quality and the optimal path will not be selected.

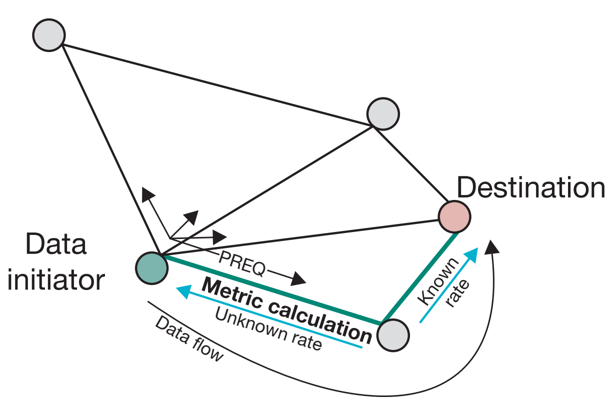

Figure 8: Path selection. Metric calculation

Path selection process' reliability

As described above, the path selection process starts with a broadcast transmission of a PREQ frame. In general, broadcast transmission is not reliable as unicast (to a specific destination) as it doesn't require an acknowledgement and it doesn't have any retry mechanism. As a result, reception of packets at the destination is not guaranteed and particularly in the mesh device that constructs the next hop of the preferred path. Moreover, since the broadcast frame is forwarded by all mesh devices until reaching the destination, its propagation might be broken over the better path at any node and be successful over some path with poor conditions.

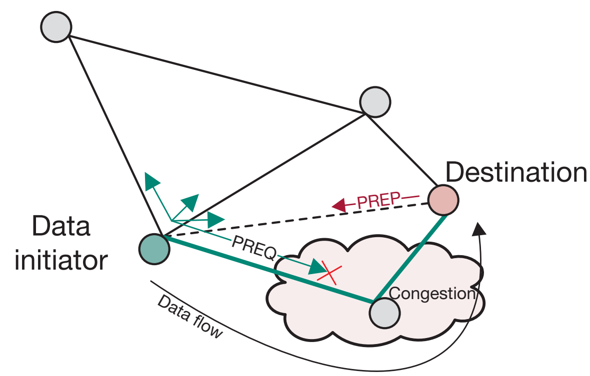

Figure 9: PREQ lost, PREP returns on the non-optimal path

The reason for such an incident can easily be explained. Figure 9 shows the data flow over the best path, which means that the air around these mesh devices is congested with the WLAN transmissions. When the path selections start, broadcast PREQ frame transmission has, as any other frame, some probability to get lost due to collision. In this case, PREP will be sent over the poor link, the path will be switched and the performance will be impacted. In the next path selection cycle, figuring the optimal path will be attempted again, it's quite possible that such a phenomena will occur again while fixating the derogated path.

WLAN mesh deployment considerations

When deciding to use a WLAN mesh solution, additional considerations should be taken into account. Those parameters will also have an impact on the overall systems behavior. A few of them are described below and should be also considered during network's planning.

Number of hops

Let's consider a scenario of a network that is contracted as the chain of devices—it should be noted that such topology might have some limitations. The limitations are reflected in the network's performance in terms of bandwidth and delay. Theoretically, this chain might be unlimited in the number of hops through it; however the data's propagation through such a network might have a very large delay accumulated when moving from device to device. Also, the maximum data throughput that will be able to flow through a large number of hops will be limited due to the air access process in the wireless network. Adding intermediate points defined as gateways, to permit data's exit though will not constrain the data to propagate from edge to edge or through a large number of hops.

Number of devices

It is known that the total bandwidth for the WLAN operation has some physical limitation value. This maximal bandwidth will be divided between all devices connected on the same channel and within the same range. Mesh flexible positioning and configuration might come in handy in cases where there is a need for a large number of devices. Dividing the network into clusters and taking leverage of the mesh range extension capabilities will increase network usability and overall performance.

Hidden nodes

When talking about large-scale or long-range networks, a key aspect of hidden nodes must be taken into consideration. The hidden node term refers to the situation when devices don't or almost don't hear each other, but still operate on the same channel and contest on access to the air. In an AP-based network, such a process is easier to control, due to the centralized nature of the network and a dedicated protection mechanism. Contrary, in a mesh network, the same protection mechanism will not always resolve the hidden nodes situation. So, network designers need to be aware of such wireless-based network problems and design the network properly.

Connection radius

The wireless network permits connections between devices even if they are located at the edge of the lowest rate sensitivity level. Such a connected device will be able to operate most of the time at the lowest modulation rates, which requires a long air time allocation and, as a result, significantly decreases bandwidth. This option is essential when this is an only way to permit some device to join the network, but can be devastating in the network that doesn't require such rescue state and might propose an alternative solution. In mesh networks, optimizing the sensitivity threshold will permit the network to operate effectively in terms of rates' usage and limit the number of connected devices to one device, hence will scatter the network's load and enlarge the total bandwidth (see Figure 10 on the following page).

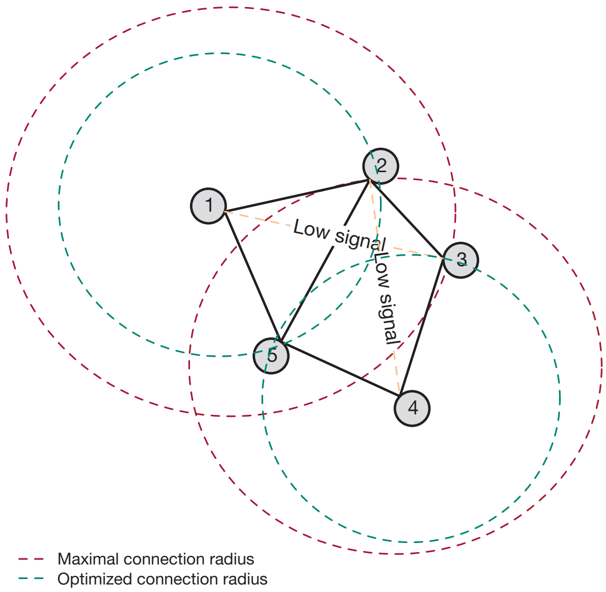

Figure 10: Network's maximal and optimized connection radius

The Wi-Fi mesh solution from Texas Instruments

The Texas Instruments WiLink™ 8 combo-connectivity device has an integrated solution for the wireless mesh network, using Wi-Fi technology. It is based on the IEEE 802.11s, MAC80211 open-source implementation. It permits a dynamic range of configurations, standalone and combined operation with other modes. Most importantly, it provides a reliable and robust implementation that overcomes many of the challenges described earlier to allow high-quality products to leverage this technology.

Although the basic 802.11s open-source implementation has been available for a few years, it has not dealt with many challenges when trying to achieve stable, high-throughput results. TI's WiLink 8 Wi-Fi-based mesh network solution enables developers to better overcome these challenges.

Path selection

As stated before, path selection is the core algorithm of the mesh network. It can make the network performance great or unusable. TI's WiLink 8 software implementation uses the "on-demand" mode as it meets the needs of most real-life scenarios. It kept its basic concepts that allows better power consumption, air utilization and dynamic deployment, but handled the reliability downfalls it has. The WiLink 8 solution will consistently find the best and the most stable path toward the destination on every path selection cycle in regular conditions. One other key improvement is adjusting the air link metric calculation also in case of obscurity of the effective rate toward the mesh device to which this calculation should be invoked as described in the section entitled "Path metric".

The example described below compares the data flow in the legacy 11n connection versus three WiLink 8 devices forming a mesh network. In both cases, the destination device is getting further away from the data source. Such a test is usually referred to as RvR (rate vs. range), where range is simulated using a variable attenuator between the nodes. In a mesh network the variable attenuator is changed linearly causing natural rate degradation and triggering the path selection protocol to alternate the data flow to the best path.

Figure 11 shows the setup and the data flow when the variable attenuator changes across the direct link and then across the second hop link.

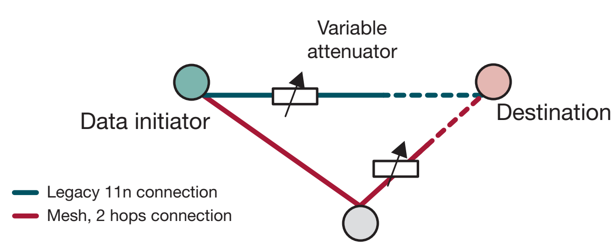

Figure 11: Basic path selection scenario

Figure 12 shows the rate selection in the different attenuation. It can be clearly seen that on the 89dB mark, a new path is selected; stopping the rate drop and allowing a stable data path for a larger range.

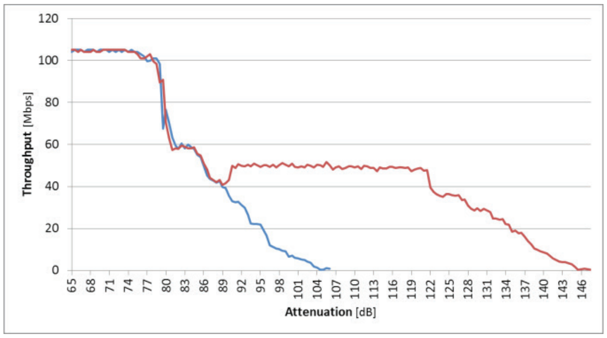

Figure 12: Mesh path selection influence on a system's performance

Referring to the reliability problems described in the section entitled "Path selection process' reliability" from which the path selection process might suffer and the wrong decision may be taken, the WiLink 8 solution provides a highly-reliable path selection process, better propagation over the network and the final correct decision also in a vulnerable network.

The following basic mesh network topology in Figure 13 describes the setup for path selection reliability analysis.

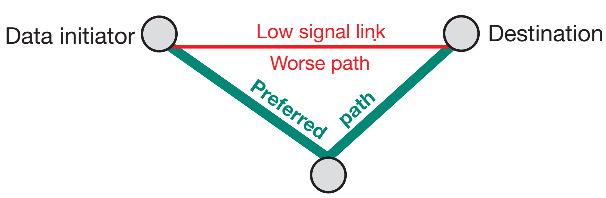

Figure 13: Path selection reliability setup

Figure 14 shows the path selection reliable behavior reflected in the stable data flow over the Wi-Fi-based mesh network.

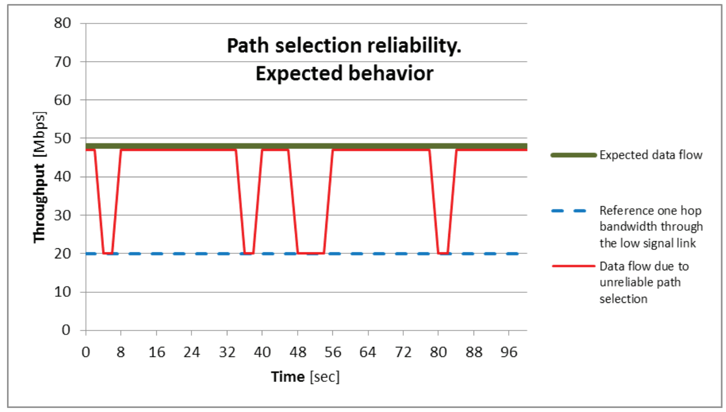

Figure 14: Path selection reliability expected behavior

Figure 15 shows the real result tested for the scenario described in Figure 13. It compares the actual throughput result with the stable path selection decision to use a two-hops path versus a pre-measured throughput as if only the direct path had been existing.

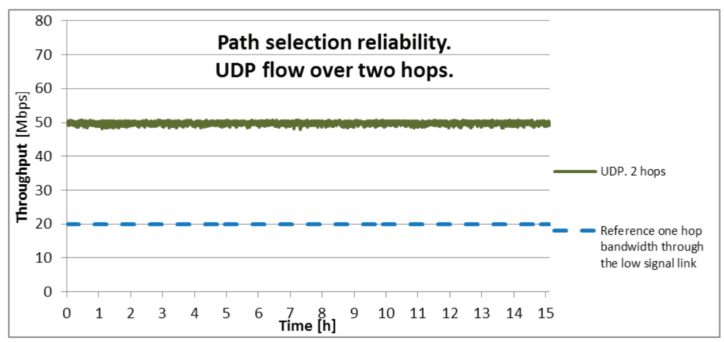

Figure 15: Path selection reliability. Actual result for the data flow over two hops for 15 hours

Bandwidth example for multiple number of hops in the mesh network

To emphasize the importance of choosing the correct Wi-Fi-based network type, an example of the mesh network, including targeted use case needs, with a multi-hop topology is presented in Figure 16 on the following page.

This example shows that, due to the inherent Wi-Fi-based network nature of air access and the bandwidth share, the network performance decreases significantly in the first hops but stabilized on the following hops keeping a bandwidth that will suit many applications.

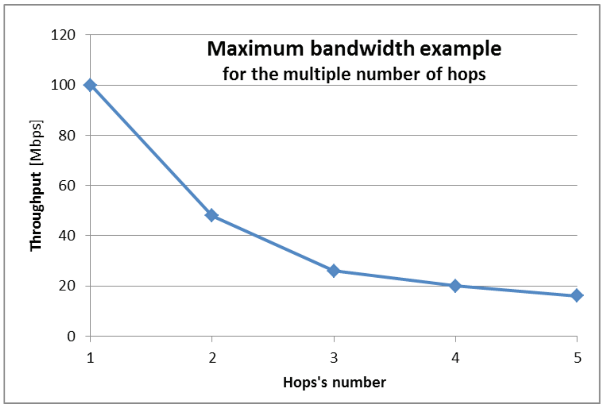

Figure 16: Bandwidth example over a multiple number of hops

Summation

There is no doubt that mesh networks are going to disrupt the way we think about Wi-Fi connectivity. Its extended range, flexibility and better network utilization is opening the door for a wide range of new applications and an improved user experience. Texas Instruments is proud to be at the forefront of this movement by providing an open-source Linux solution that is robust, reliable and easy to integrate on both new and existing WiLink 8-based solutions.

For more information on TI's Wi-Fi mesh solution, please visit: **www.ti.com/wilinkmesh**

References

[i] IEEE 802.11-2012 specification document section 13.10, p. 1382.

[ii] IEEE 802.11-2012 specification document, section 13.9 p. 1381.