Qualcomm Hy-Fi® Total Configuration Algorithm (TCA) for Hybrid Devices

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1. Introduction

The demand for ubiquitous connectivity with high data rates in the home is rapidly increasing. It is driven by a combination of different devices and applications such as set top boxes, DVRs, streaming video, smartphones, and tablets, etc. In this paper, we describe a solution that would help satisfy such stringent demand. We describe how to use hybrid devices to form a hybrid network that maximizes data throughput and coverage within a home. Then we discuss the challenges of setting up the hybrid networks followed by the solution provided by Qualcomm Hy-Fi® Total Configuration.

2. Hybrid Devices and Networks

Home network connectivity can be provided by either *wired* or *wireless* access. Existing popular wired technologies include coax, Ethernet, and power line communications (PLC). While coax and Ethernet provide reliable and high bandwidth access, most homes are not pre-wired with these in every room and in many parts of the world it is difficult and expensive to retrofit.

PLC provides the most flexibility in terms of ubiquitous outlet availability in homes without requiring dedicated wires for data, making it an attractive choice for wired access in any home networks. The PLC data throughput is subject to electrical wire channel conditions between the outlets and also the noise generated on the wires by other electric appliances. Obviously, any wired communication requires actual wires to be connected to the source or destination device, which limits the placement of the devices, and once placed, they cannot be moved.

On the other hand, wireless access in the unlicensed spectrum, such as Wi-Fi, offers the convenience of untethered connectivity anywhere—provided that the devices are in range of the access point. The user experience over wireless access is also subject to interference from neighboring access points, interference from appliances (such as cordless phones and Bluetooth devices) and variations in the signal strength from the access point that the devices can receive. The signal attenuation depends largely on the obstructing materials that the signal needs to penetrate through, of which concrete walls and metal prove to be especially challenging.

It is worth noting that the coverage provided by PLC and Wi-Fi may be uncorrelated. For example, while a concrete wall may severely attenuate a Wi-Fi signal, the PLC outlet may be able to provide excellent throughput. A hybrid device, such as Qualcomm Hy-Fi®, is designed to take advantage of the complementary nature of both mediums where multiple access technologies can be used simultaneously to carry data, and provide redundancy and diversity gain.

To support such devices, IEEE has been working on a standard called IEEE 1905.1 that allows interoperability of devices manufactured from different vendors. The 1905.1 standard is an abstraction layer on top of different access technologies (e.g., IEEE 802.11, IEEE 1901, Ethernet, and MoCA) that enables data to be sent using these interfaces simultaneously. It also provides hooks for easy configuration, control and troubleshooting.

2.1. Hybrid Network Example

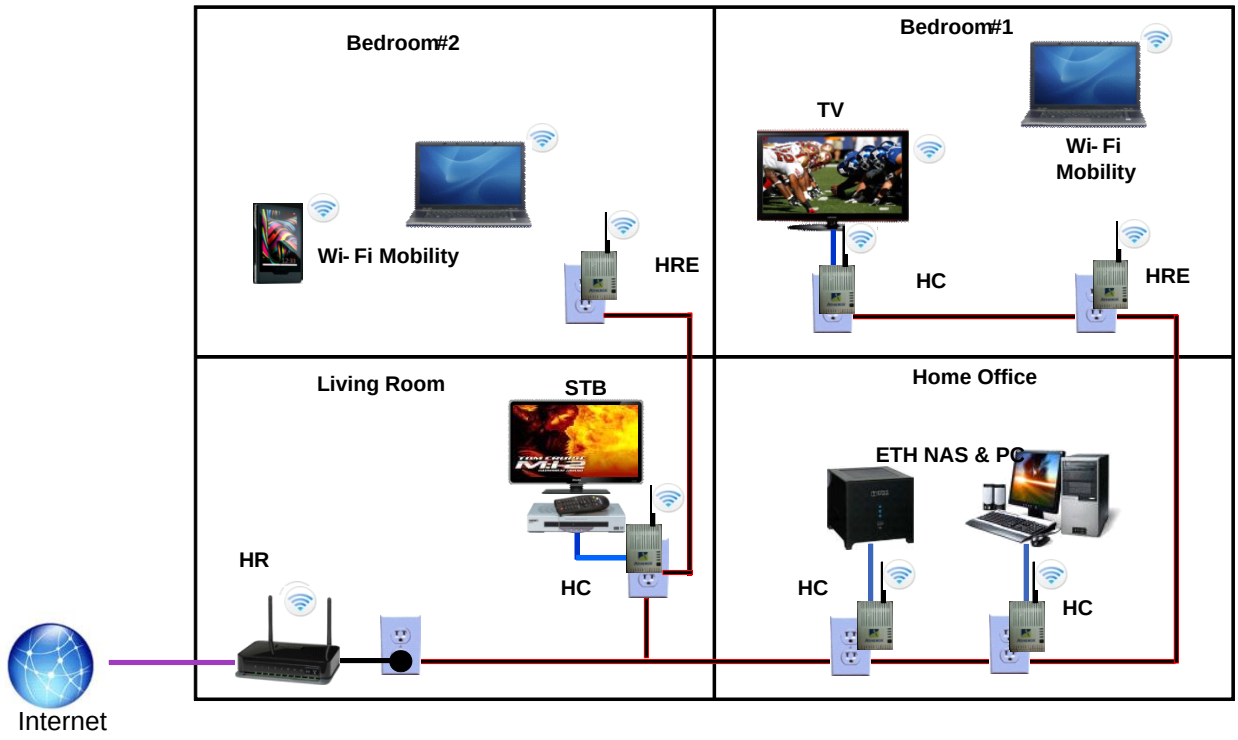

Figure 1: A Home Connected by Hybrid Devices

Figure 1 shows a typical hybrid network which is comprised of several hybrid devices. A typical setup is with a hybrid router (HR) connected to the gateway (e.g., cable or DSL modem) and also plugged into the power outlet (to get both power to the device and connect to the PLC network at home). The HR provides Internet access to the rest of the devices in the network via PLC and Wi-Fi. In each room, one or more hybrid devices (called hybrid clients or HCs) are also used, depending on the use case. The HC connects to the HR via PLC, Wi-Fi, or both. For example, in Bedroom #1, one hybrid client is connected to the TV via Ethernet. This hybrid device has its STA enabled so data arriving from both Wi-Fi and PLC can be sent to the TV over Ethernet. The other hybrid device in the same room has its AP enabled to extend Wi-Fi coverage for fixed and mobile wireless devices. Another type of device is called a hybrid relay (HRE), which extends the Wi-Fi coverage by enabling its access point.

As an example, a typical single story U.S. home was used to illustrate how hybrid devices increase the home network performance. Figure 2 through Figure 5 show a comparison of path loss and Wi-Fi data rate available between two setups—one with a single AP and one with multiple hybrid devices with AP capabilities. The x-axis and y-axis are in meters in all the plots shown in this document. The color shows the pathloss or data rate. Red means lower pathloss, or higher data rates, while blue means the opposite. It's obvious the network of hybrid devices provides a much more uniform coverage and higher Wi-Fi

throughput throughout the whole house by providing additional access points that extend the Wi-Fi coverage.

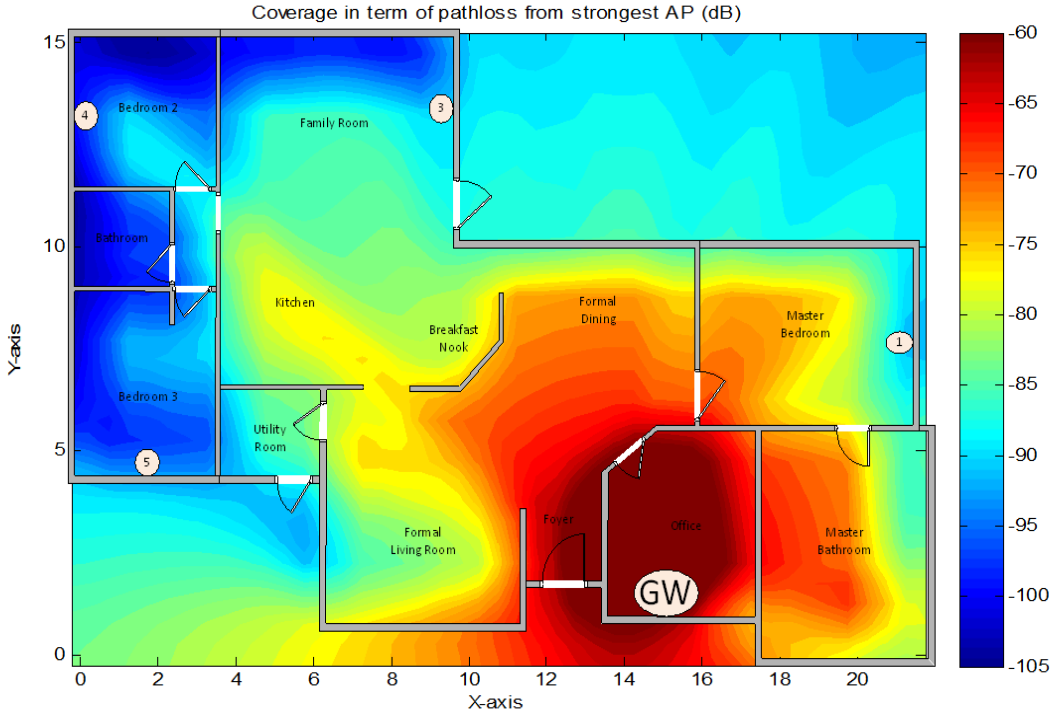

Figure 2: 5GHz Path Loss (dB) with Single AP (marked as GW)

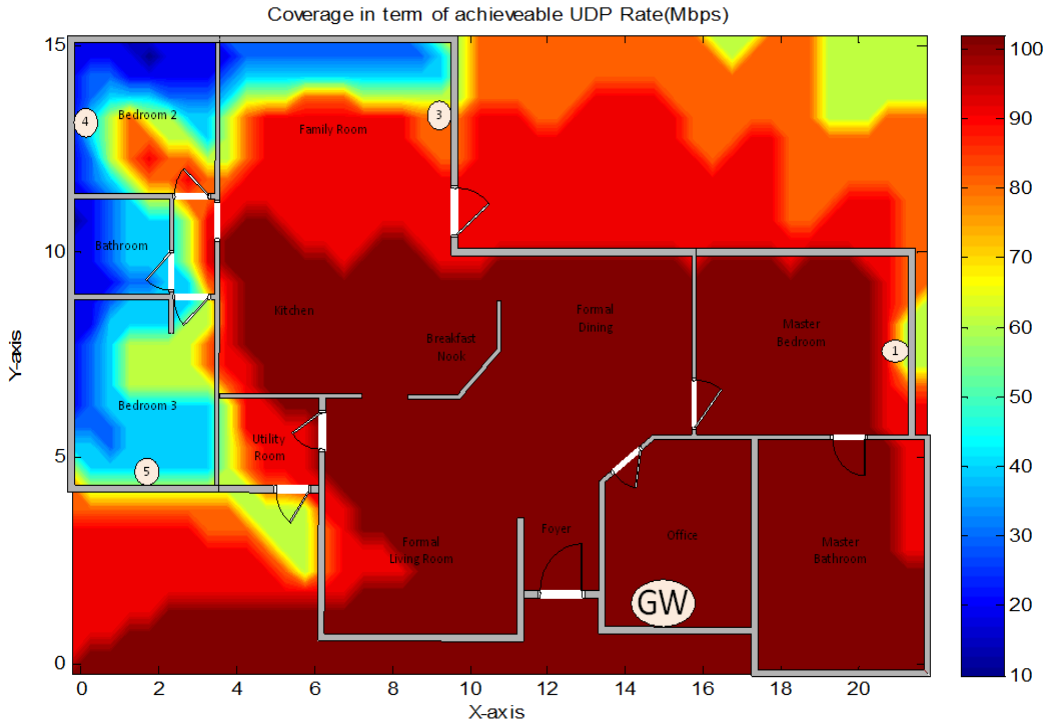

Figure 3: 5GHz Data Rate (Mbps) with Single AP (marked as GW)

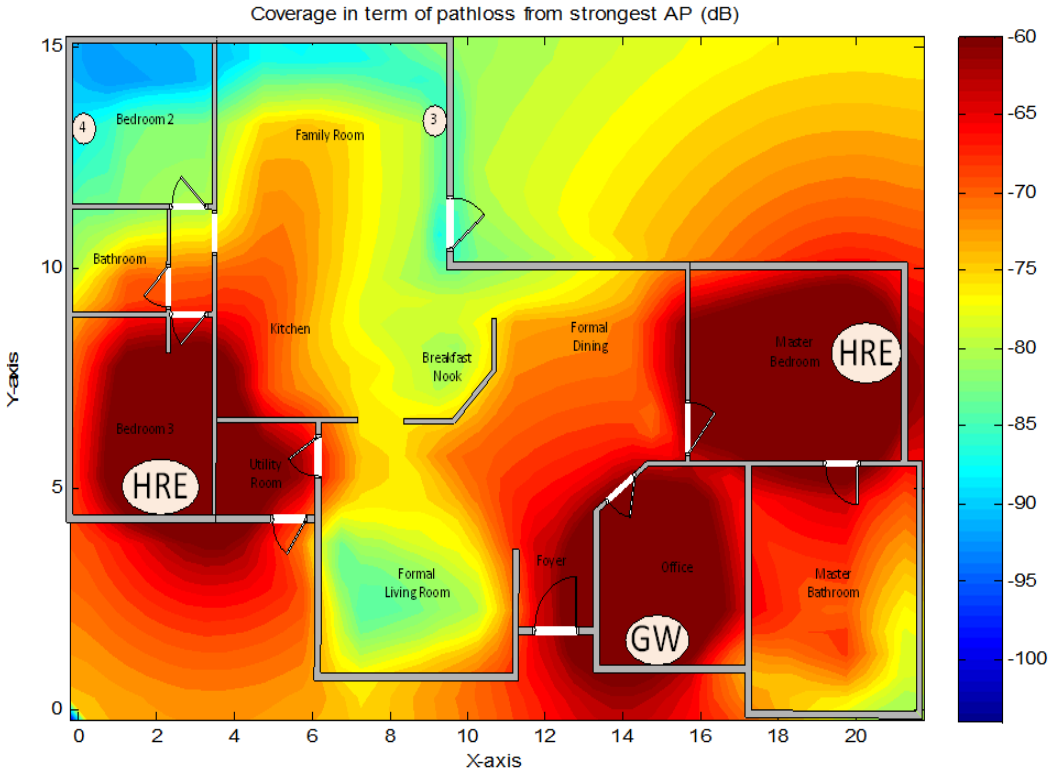

Figure 4: 5GHz Path Loss (dB) with two HREs and one HR (marked as GW)

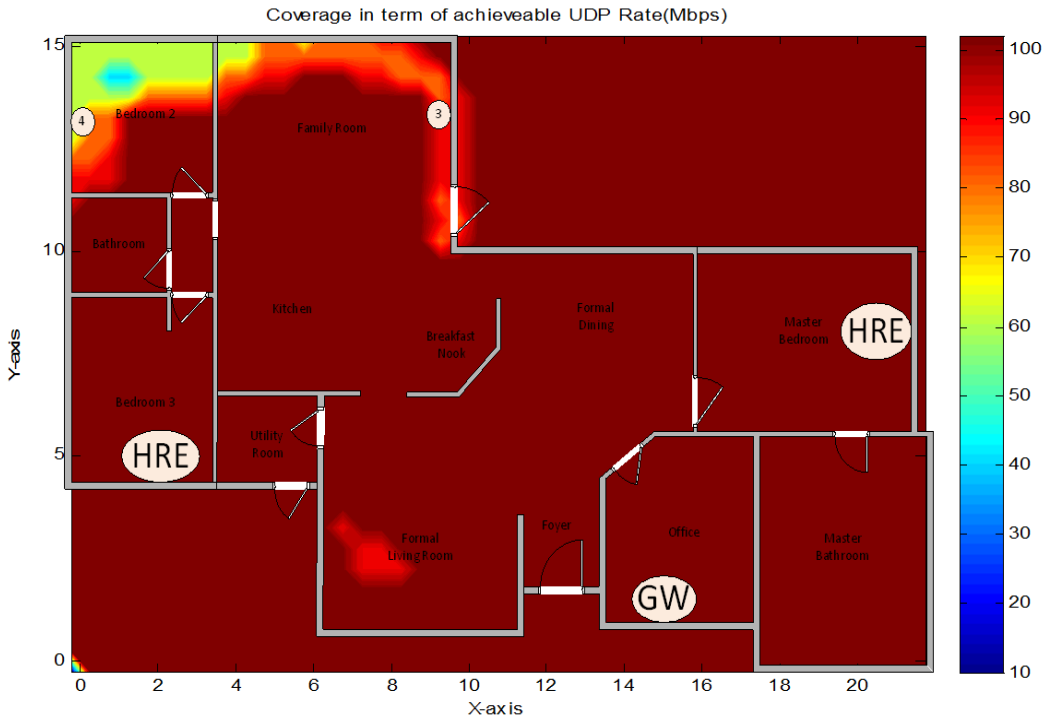

Figure 5: 5GHz Data Rate (Mbps) with two HREs and one HR (marked as GW)

3. Hybrid Network Configuration

While hybrid devices provide multiple versatile options in forming networks that can satisfy the needs of various homes in which they are installed, the multitude of complex configuration options can also overwhelm end users and are challenging to properly optimize—even for trained technicians. The following lists provide an example of configuration options that may need to be adjusted in a hybrid device and network:

- Security credentials on each access interface
    - Security features ensure confidentiality of user data and restrict network access to only legitimate users. If not configured correctly, others can eavesdrop on the user data and may also be able to connect to the network without the owner's permission.
- Interfaces to enable
    - Wi-Fi Station (STA)
    - Wi-Fi Access Point (AP)
    - These interfaces have different properties. An STA is used to receive data and an AP is used to extend wireless coverage. It is not trivial to determine for a specific device whether these interfaces should be enabled. For example, if the device detects that the wireless coverage is insufficient, it may enable the AP to extend the wireless coverage depending on other factors such as the backhaul quality of the device to the home router, which connects to the gateway for Internet access.
- Wi-Fi operating channels
    - There are different channels available on each band with different bandwidths and not all of the channels are equal in terms of channel quality. For example, there could be heavy interference from a neighbor's wireless network on a specific channel, which a user will want to avoid. Also, in the case of multiple APs in a home network, the channels must be selected appropriately to maximize coverage.
- Bridging decisions
    - Since a hybrid device contains multiple interfaces, packets can be bridged between the interfaces. When there are multiple interfaces connected between two hybrid devices, care needs to be taken to avoid broadcast storms and looping created by incorrectly routing the packets while guaranteeing that all devices in the network are reachable and preserving the diversity of paths provided by the hybrid devices.
- Configuration of APs
    - In a hybrid network, it may be necessary to enable multiple APs to provide good wireless coverage to mobile devices. Each of these APs will need to be configured consistently. This configuration is supported by the IEEE 1905.1 standard where a single AP is a Registrar and the rest of the APs are Enrollees which will copy their configuration from the Registrar.

To address the above challenges, Qualcomm developed an algorithm called the Qualcomm Hy-Fi® Total Configuration Algorithm, which will be discussed in the next section.

4. Qualcomm Hy-Fi® Total Configuration Algorithm (TCA)

The purpose of Total Configuration Algorithm (TCA) is to automatically configure all the hybrid devices to maximize the coverage, throughput and reliability without any user intervention. This greatly enhances the user experience and makes setting up a home network easy and straight forward. When using Wi-Fi and PLC products available in the market today, the user has to manually configure each technology separately. Using TCA on hybrid devices, all the user has to do is the following:

- Plug in the WAN connection to one hybrid device
- Plug in other devices throughout the house one by one, at places likely for data usage. On each device, the user pushes the push-button, and the push-button of another in-network device within a time out (~2min). The push-button process is used to join the device securely to the network. And the network is automatically configured by TCA.

TCA is responsible for the following:

- Configuration and security
- Topology and connectivity
- Personality (Wi-Fi STA and AP configuration)
- Wi-Fi channel selection
- Adaptation to changes

4.1. Configuration

There are two security features that need to be considered in the home network. The first feature ensures that only legitimate devices can be connected to the home network (e.g., your neighbor cannot connect to your own home network). The second feature ensures that others cannot eavesdrop on user data in the home network. Both of these issues are addressed by the security provided by the underlying access technology. However, for these security features to work correctly, each access technology has to be configured correctly—a process which usually involves setting up network I.D. and password, etc. on each access technology—a very cumbersome task for the user.

TCA automatically generates randomized Wi-Fi credentials for the HR for which the user may override if desired. For other devices, the AP Wi-Fi credentials are configured using the 1905.1 AP-autoconfiguration procedures, where one AP is configured as the Registrar and the rest of the APs (enrollees) copy the configuration from it. The security credentials of the STA and PLC of the device are already set up via the push button method when the user joins the device to the network.

4.2. Topology and Connectivity

TCA constructs the topology of the network automatically for all the devices that are connected to the network. For example, TCA knows which device is connected to the gateway and will treat that device as the “root” of the network through which all Internet traffic will pass. For other non-root devices, TCA ensures that the STA (if enabled) of each device is associated with the appropriate AP. Since there may be more than one AP enabled in the network, this decision is not trivial and may not be static. For example, radio condition changes over time, connectivity between devices could be lost either due to hardware failure or heavy interference, etc. If the topology is not configured correctly, loops could be formed. For example, if two devices have both their APs and STAs enabled, their STA and AP may associate with each other in a circular manner that creates a loop.

4.3. Bridging Decision and Packet Loop Prevention

Since there may be multiple connections between devices and multiple paths (a selection of interfaces) between two devices, TCA also has mechanisms to prevent loops from forming within the home network.

A hybrid device contains multiple interfaces, potentially allowing packets to be bridged between its interfaces. As there are multiple interfaces connected between two hybrid devices, care needs to be taken to configure the bridging of the packets to ensure the following:

- No Broadcast Storm
    - When a broadcast packet reaches an interface and the device decides to broadcast that packet on multiple interfaces and the same procedures repeat in the other receiving devices, this could create a broadcast storm where packets are spawned indefinitely. This will bring down the network.
- No Looping of Packets
    - A single non-looping route is needed for each unicast packet. Otherwise, a packet can traverse in the loop forever, never reaching its destination. Such looping will eventually exhaust the processing power of the devices involved.

4.4. Personality

The goal of personality determination is to set up a reliable network throughout the whole house considering both the wireline coverage (e.g., the devices connected by PLC) and wireless coverage (e.g., tablets being used throughout the house). TCA evaluates many different factors affecting coverage and performance of the whole network such as connection quality between the devices on each interface, channel condition, etc.

Intuitively, one may think it is best to enable all the wireless and wireline interfaces to provide as much bandwidth and coverage as possible. However, there are situations where *less* is better as shown in the following example. In Figure 6, we show a home network with two APs enabled and the path loss from

the AP with the strongest RSSI. Device 2 is connected to the gateway and its PLC and AP are enabled. Device 1 is connected to Device 2 via PLC and Device 1's AP is enabled. Figure 7 shows the available data rate at each location of the house, assuming that a client at a particular location will always associate with the AP that has the lowest path loss (highest RSSI). It can be seen that the Wi-Fi data rate is ~60Mbps almost throughout the whole house.

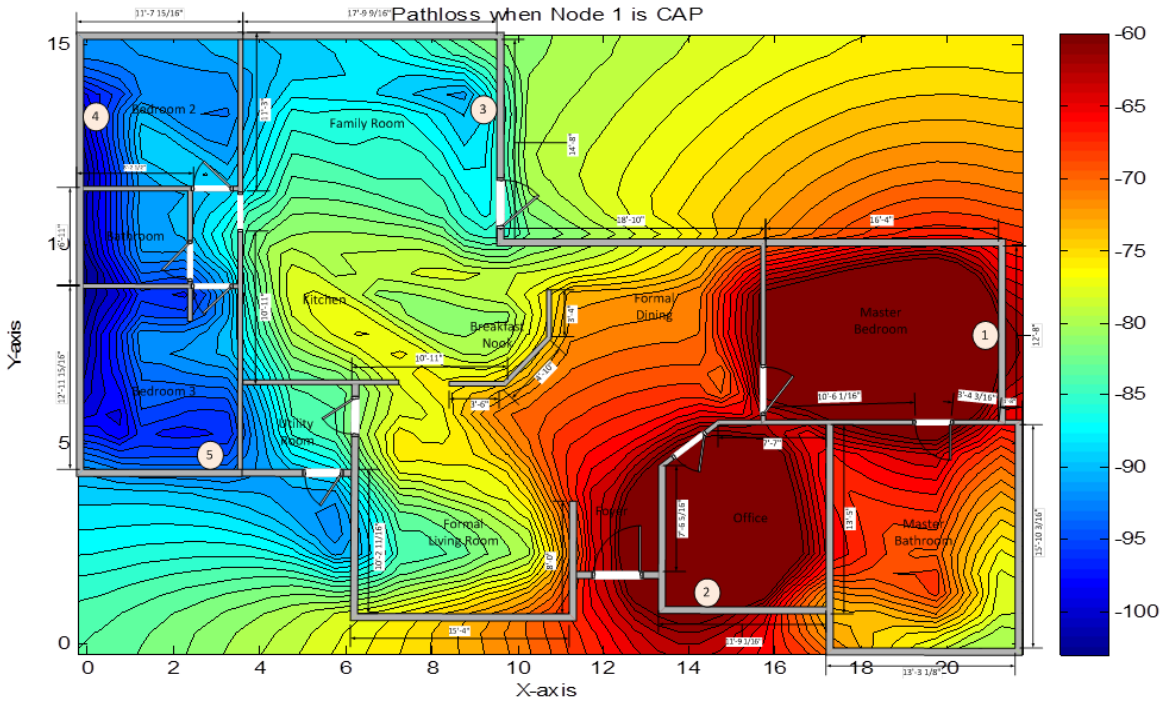

Figure 6: Topology with only 2 APs (HRE + AP) Enabled (values shown in dB)

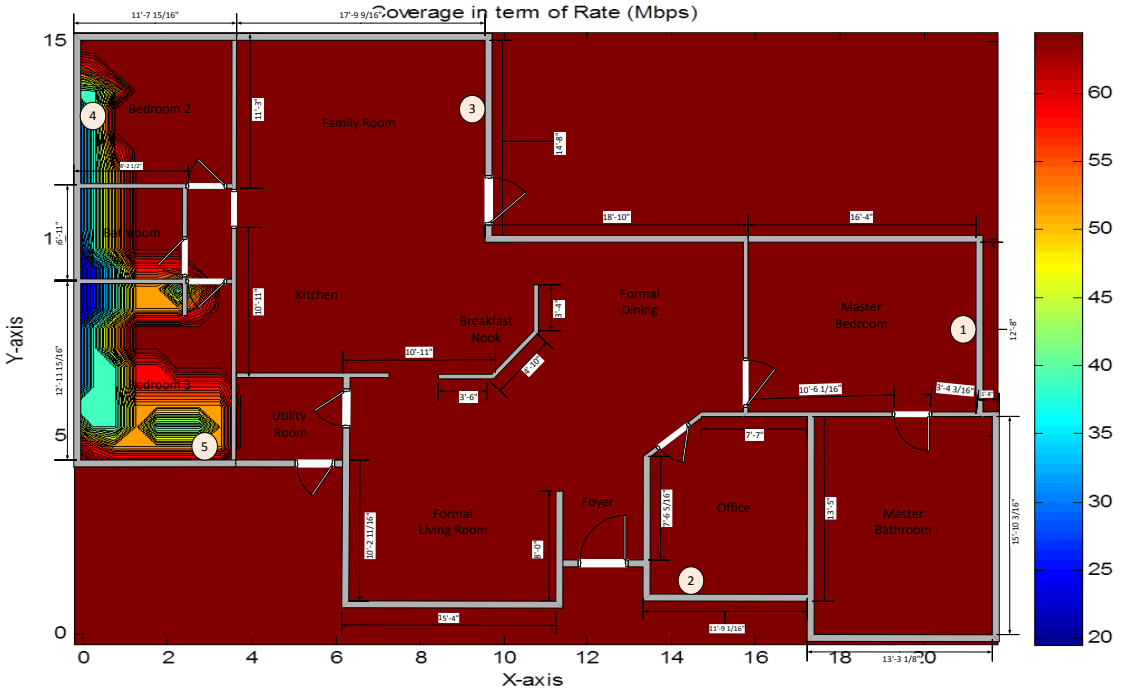

Figure 7: Topology with only 2 APs (HRE + AP) Enabled (Wi-Fi Data Rate shown in Mbps)

In Figure 8, we show the same house but with an additional device (Device 5). Device 5 is connected to Device 2 via PLC and Device 5's AP is enabled. Figure 9 shows the available data rate at each location of the house. It can be seen that the Wi-Fi data rate was reduced to 50Mbps in almost 1/3 of the house despite having one more device providing service. So with one more AP enabled, the network actually performs worse. The reason for the degradation in this case is that the PLC link between Device 5 and Device 2 is limited to ~50Mbps. Yet in the blue area, the Wi-Fi clients will associate with Device 5 and be served at a lower data rate.

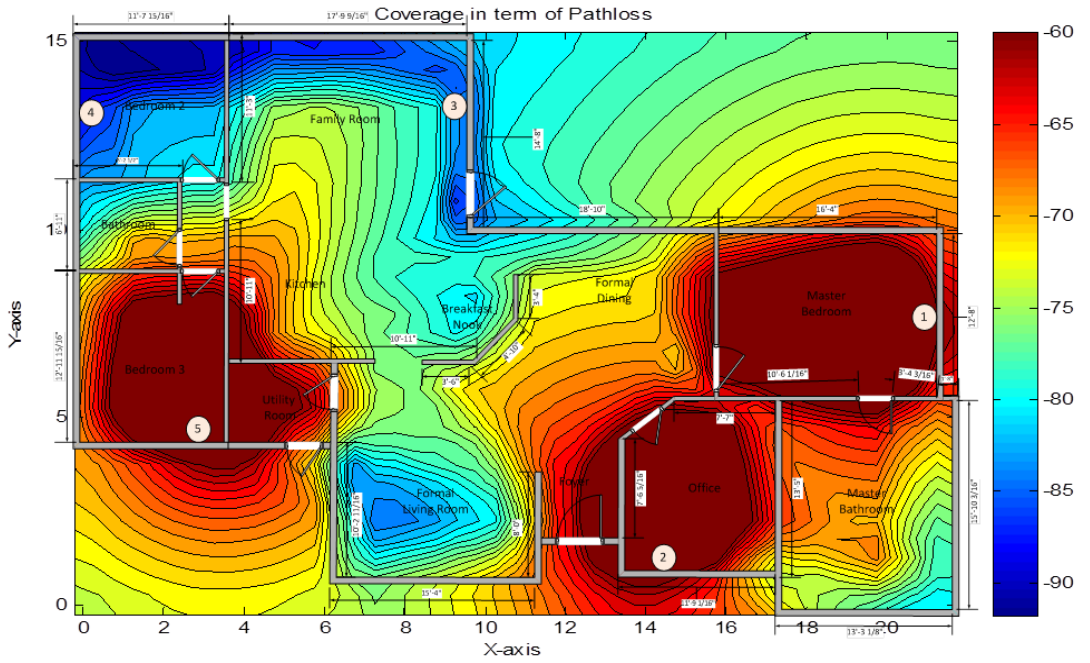

Figure 8: Topology with only 3 APs (2 HREs + HR) Enabled (values shown in dB)

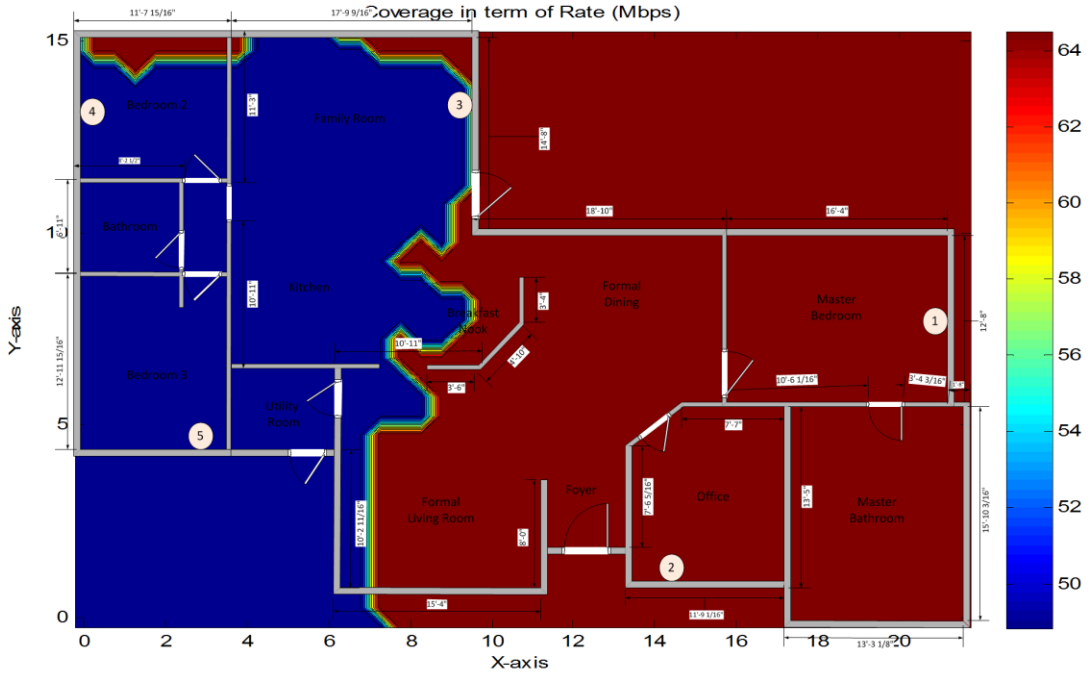

Figure 9: Topology with only 3 APs (2 HREs + HR) Enabled (Wi-Fi Data Rate shown in Mbps)

In general, each hybrid device has a PLC interface which is enabled by default. Each (single band) hybrid device also contains an STA and an AP. Furthermore, each dual band dual concurrent (DBDC) device contains two STA-AP pairs which can operate in both bands simultaneously. Since the device may disable/enable these interfaces individually, it is not trivial to determine which Wi-Fi interfaces the device should disable/enable.

For a single band device, there are four combinations (or personalities):

- STA OFF and AP OFF (Wi-Fi Disabled)
- STA OFF and AP ON (Hybrid Range Extended [HRE] with STA disabled)
- STA ON and AP OFF (Sink)
- STA ON and AP ON (Hybrid Range Extender [HRE] with STA enabled)

For a DBDC device, there are even more combinations between the two bands. One can envision that if the interfaces are enabled/disabled arbitrarily, the performance will suffer and this is where TCA will help.

Figure 10 shows an example home network using hybrid devices which assume different personalities and form a home network to provide both wireline and wireless coverage. Note the HRE extends the Wi-Fi coverage of the HR to serve the mobile device that is far away from the HR.

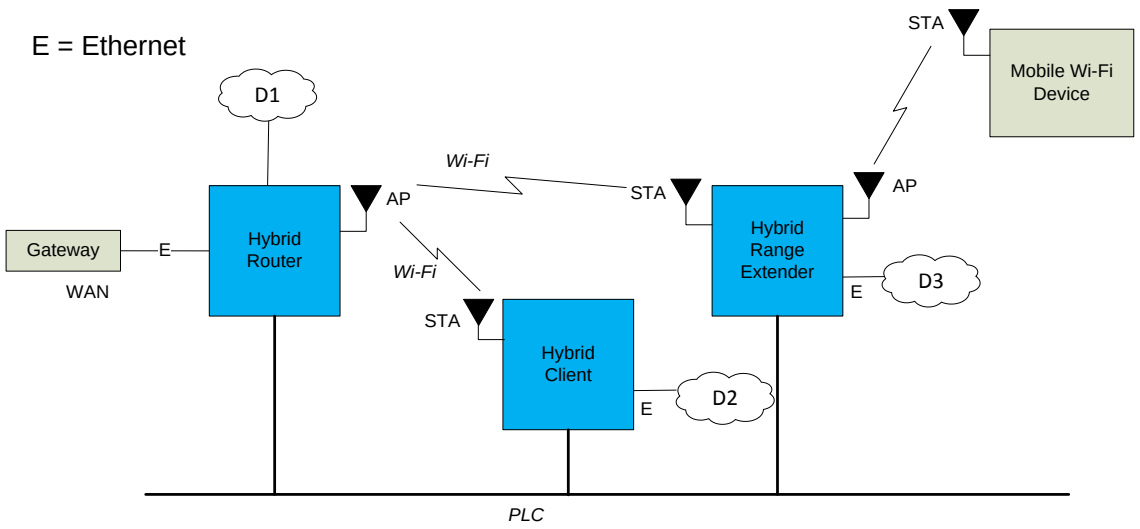

Figure 10: Simple Topology with a Hybrid Router

4.5. Wi-Fi Channel Selection

When an AP transmits on a channel, it creates interference to other APs that are transmitting on the same channel. Therefore, a careful channel selection should be made in order to minimize such interference. TCA selects an appropriate frequency band and channel for each device to provide the highest data rate capacity throughout the network. There are many factors affecting which channel is selected and TCA takes into account the capacity versus coverage trade-off. For example, an HRE that has its STA enabled has to use the same channel as the HR, which reduces the Wi-Fi capacity whereas an HRE that has its STA disabled can use a different channel than the HR, which increases the Wi-Fi capacity. Another consideration is an HRE with its STA enabled may use Wi-Fi as an extra backhaul to the HR in addition to PLC whereas an HRE with its STA disabled is limited to using the PLC as the backhaul to the HR.

4.6. Adaptation to Changes

In the home environment, many things can change—radio channel condition, failure of an interface, interference from other devices, location of the devices (user moves the devices), connecting/disconnecting an end client, etc. TCA is designed to adapt to all these changes and to come up with a good network topology that provides good data rates and Wi-Fi coverage without any user intervention. TCA monitors the network continuously and adapts to any long-term changes when needed.

TCA also has mechanisms to ensure the stability of the network and to avoid instability caused by temporary situations. Without TCA, the user will have to detect and correct these issues manually, which will be quite cumbersome and prone to errors resulting in performance degradation.

5. Conclusion

By using hybrid devices, maximum throughput and coverage can be achieved to satisfy the demand of both wired and wireless end devices. Qualcomm Hy-Fi® can be readily deployed in any home since it uses existing power line networks within the home and no additional wiring (e.g., Coax, Ethernet, etc.) is needed.

Hybrid network requires multiple hybrid devices working together to maximize performance and these devices need to be set up appropriately. When the configuration can be done manually, it would not be user friendly. TCA eliminates the chore of manually configuring the individual devices by configuring different aspects of the devices automatically. That greatly simplifies network setup and enhances the user experience. Moreover, TCA adapts to changes automatically so it’s essentially tuning the network in the background continuously and making adjustments when and if necessary. It ensures that the user can get the best performance out of the devices given their locations, which enhances the overall user experience of fixed and mobile devices within the home.

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