The Evolution of Wireless Home Networks

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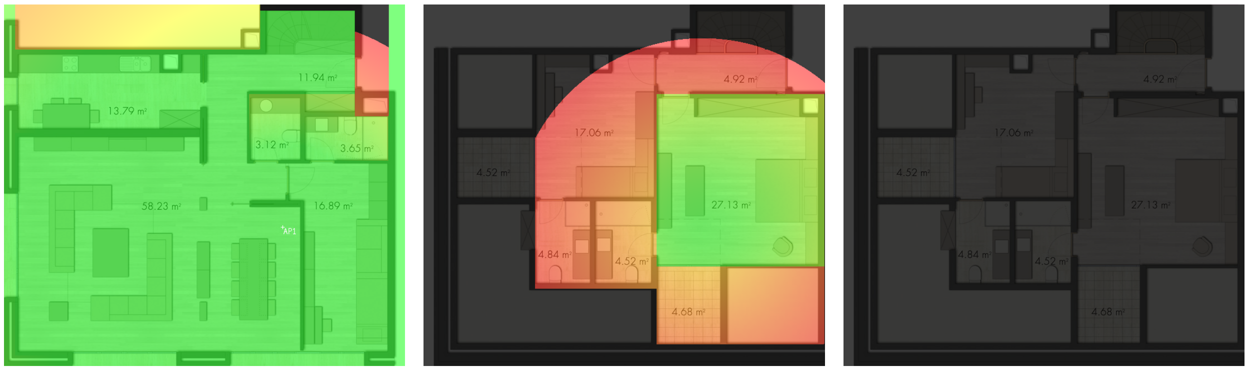
Airties Wireless Networks

Introduction

As wireless consumer devices that facilitate high definition video streaming or on-line gaming gain popularity, the need for pervasive, high capacity wireless home networks becomes increasingly more pressing. Today, one of the primary limitations of home WiFi networks is coverage. Most setups provide WiFi connectivity to all devices in the home via a central wireless Access Point (AP); these setups mostly have "null" zones where the reception is very limited such as bathrooms, corners, the far room down the hall. Furthermore, the bandwidth available to WiFi devices connecting from these zones is quite low, which severely limits the functionality of data-hungry applications such as video streaming. Increasing the signal strength of the central AP not only increases the cost and environmental impact of the system, but it cannot always completely solve the problem given legal limits on the emitted signal power.

	Broadband Households			
	Total IP Devices	**Netflix Streaming**	**Hulu Plus**	**Amazon Prime**
Smart HDTVs	0.36	0.62	0.80	0.66
HDTV w/o Internet	1.05	1.17	1.26	1.33
Non-HDTV	1.00	0.91	0.78	0.85
Total TVs	**2.41**	**2.69**	**2.84**	**2.84**
Notebook/Laptop PC	1.42	1.91	2.03	1.88
Desktop PC	1.13	1.19	1.19	1.30
Google Android Smartphone	0.52	0.88	1.08	0.94
Apple iPhone	0.44	0.77	0.77	0.64
Stand-alone Blu-Ray Player	0.44	0.71	0.88	0.78
Nintendo Wii gaming console	0.38	0.57	0.64	0.60
Smart HDTV	0.36	0.62	0.80	0.66
iPad tablet	0.30	0.50	0.63	0.49
Microsoft Xbox 360 gaming console	0.29	0.55	0.72	0.52
Kindle tablet	0.26	0.46	0.57	0.66
Sony PS3 gaming console	0.22	0.37	0.56	0.42
Other tablet	0.21	0.33	0.50	0.38
Streaming Media Player	0.17	0.36	0.59	0.47
Microsoft Windows Mobile Smartphone	0.13	0.15	0.29	0.17
Total Connected Devices	**6.28**	**9.37**	**11.26**	**9.92**

Table 1: Survey data representing the number of broadband-enabled household devices in the US [3]. The "Total IP Devices" column provides statistics regarding all broadband households, while the Netflix Streaming, Hulu Plus and Amazon Prime columns pertain specifically to the subset of users who use these premium OTT video services.



(a) Floor 1 (b) Floor 2 (c) Floor 3

Figure 1: Received Signal Strength Indication (RSSI) in a sample three-floor apartment using a single wireless AP transmitting at the maximum EIRP of 30 `dBm` at 5 GHz. Areas are colored from green to yellow to red to indicate their RSSI, with black areas indicating complete outage.

Challenges of Home WiFi

Path Loss

WiFi systems use the IEEE 802.11 standard, which regulates wireless systems to use the 2.4 GHz and 5 GHz frequency bands for signaling. The coverage of (or inversely, the path loss experienced by) such signals can be predicted using one of many models that attempt to formulate their behavior. A model commonly used for this purpose is the *log-distance path loss model* [2], which describes the average received power $\overline{P}$ (in `dBm`) at a distance d (in meters) from the transmitter, in free space, ignoring the multipath propagation effects, as:

$$\overline{P}(d) \quad = \quad P_t + G_t + G_r + 20log_{10}\frac{\lambda}{4\pi d} \qquad (1)$$

where P_t is power radiated from the transmitter, and G_t and G_r are the gains of the transmitting and receiving antennas, respectively. Note that according to this model, signal strength decreases logarithmically with distance -in free space- as one moves away from the transmitter.

In practice, wireless signals encounter attenuation as they propagate, not only with distance, but also due to reflections from surfaces of objects in the environment or refraction when going through walls, doors, etc. Because waves attenuate much faster at higher frequencies, the communication range and therefore the coverage area at the 5 GHz frequency band have even a greater limitation compared to the respective values when operating at 2.4 GHz.

Power Limitations

While most APs try to maximize coverage by increasing P_d in Eqn. (1) by maximizing $P_t + G_t$, the European Telecommunications Standards Institute (ETSI) and the United States Federal Communications Commission (FCC) impose strict limitations on the amount of radiated power for WiFi devices. Called Effective Isotropically Radiated Power (EIRP), this sum shall be limited to a specific value that is dependent on frequency band and country of operation. In the EU, ETSI defines the harmonized standard for this value to be +20dBm in the 2.4 GHz frequency band and at most +30dBM at 5 GHz [1]. Consequently, increasing $P_t + G_t$ in Eqn. (1) is not feasible to beyond a standard value.

More sophisticated APs also apply Multiple-Input Multiple-Output (MIMO) techniques, e.g. 2x2, 3x3, 4x4 diversity, spatial multiplexing or digital beamforming (standardized as part of the IEEE 802.11ac standard), in order to maximize range. While these techniques certainly help with increasing coverage, sufficient coverage in a large or even mid-sized house is simply not possible with a single AP mainly due to the cap on total device radiation. Figure 1 shows an example of wireless coverage in a multi-floor home environment. Note that coverage is greatly reduced past the rooms (and floors) immediately neighboring the AP location.

Interference

As the Wi-Fi medium is a shared communication environment, WiFi networks are prone to interference both from other WiFi devices and from non-WiFi sources. Smarter wireless APs try to minimize interference with other WiFi networks by scanning the available channels and choosing the one on which they hear the least amount of activity. However, this method for interference avoidance may not always be practical in home deployments. For example, consider the Gateway (GW) in Fig. 2 that is placed in a central location in the home to maximize coverage, but because of this it is quite far from any of the outer walls (and thus neighboring homes), and because of this placement it is less likely to hear and avoid the WiFi activity in the neighboring homes; the Client and STB1 that are connected to it however are much closer to neighbors and are thus more prone to interference from neighboring WiFi networks.

WiFi devices also suffer from interference generated by non-WiFi devices such as household appliances or radar systems. 5 GHz radar interference in particular is regulated by the ETSI; WiFi devices operating on "high power" 5 GHz channels are required to watch out for radars operating in their channel, and quickly vacate the channel and move to a non-radar ("low power") or radar-free channel when such activity is detected. The complexity of such a detection system and the necessity to sooner or later vacate radar channels often results in 5 GHz WiFi APs piling on the low-power non-radar channels. APs stuck in low power channels must deal with both greater interference from all the other APs similarly stuck there, as well as with a smaller transmission power limit (less than a quarter of that which could have been used on the radar channels).

Shared Wireless Medium

In the home, all WiFi devices operate at the same channel in order to be able to communicate; this means they share the *airtime*. The airtime consumed by each device is essentially the amount of time they take to send (or receive) their data. Since WiFi devices must all share the same finite airtime budget, devices with a poor connection not only suffer themselves but also hurt other devices in the same network as they hog the air to get a relatively low amount of data across.

Figure 2 shows an example of a traditional star network topology, where the home Gateway (GW) is also an AP via which all WiFi devices communicate with the outside world and with each other. In this AP-centric star topology, devices must talk to each other via the AP.

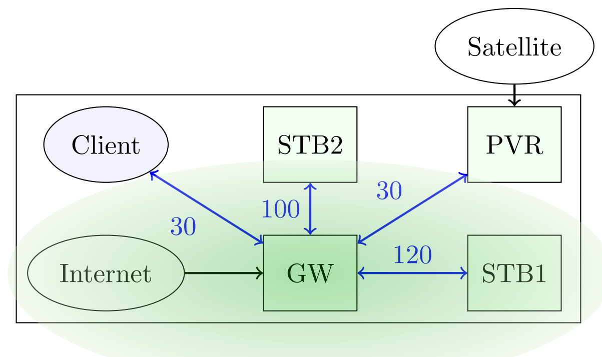


Figure 2: A typical home WiFi network topology. Data is delivered to the home via Internet and Satellite connections in different parts of the home, and is consumed by a variety of wireless devices such as STBs and mobile clients. The high throughput coverage zone of the AP is shown as a green gradient.

In the home network in Figure 2, when any WiFi client needs to stream high quality video recorded on the PVR, the data must first be sent from the PVR to the GW and then from the GW to the client. E.g., when the Satellite PVR is transferring content to STB2, the achievable capacity on this transfer is a function of the capacities on these respective links:

$$link_{PVR \rightarrow STB2} = \frac{1}{\frac{1}{30} + \frac{1}{100}} \approx 23 \text{ Mbps} \qquad (2)$$

Eqn. (2) indicates that the achievable capacity is inversely related to the airtime used to transfer data across, where the airtime to transfer data on two consecutive links is added as these links share the wireless medium and cannot be active simultaneously without interfering with each other.

Inter-Device Data Transfer

As briefly mentioned previously, connectivity issues in the home WiFi are significantly aggravated when data needs to be transferred between two devices in the same WLAN. Because of the star topology formed in the single-AP WLAN, all traffic between wireless clients must be forwarded by the AP (in most home scenarios, this AP is the Gateway). In Fig. 2, when the STB is streaming video from the PVR, the 100 Mbps and 30 Mbps link speeds of the PVR and STB with the AP actually result in a 23 Mbps end-to-end link (Eqn. 2), which, if used to stream high quality 20 Mbps 1080p content will consume almost all the airtime in the network, disrupting -and itself being disrupted in the presence of- any other wireless traffic.

Table 2 shows estimated airtime requirements for transferring data between two devices in the WLAN shown in Fig. 2; the data shown indicates that even a single HD Satellite channel delivered to the STB consumes close to half the total available airtime. When combined with the information presented in Table 1, which showed that most homes have on average about 1 SDTV and 1.5 HDTVs and those using premium OTT video services have between 9-11 IP devices that utilize such services, the data in Table 2 hints that in a home with a single AP, despite seemingly acceptable individual connections, a handful of wireless devices will exhaust available airtime, allowing at most 2-3 out of 9-11 wireless IP devices to operate simultaneously.

Device	Usage	Data	Link	Airtime
STB1	OTT	6 Mbps	120 Mbps	0.05
STB2	OTT	6 Mbps	100 Mbps	0.06
STB2	via PVR	10 Mbps	23 Mbps	0.43
Client	via PVR	10 Mbps	15 Mbps	0.66

Table 2: Sample airtime requirements for the devices in the home network shown in Figure 2.

AirTies Mesh

One technology that aims to solve the above-mentioned issues is the *wireless mesh*. Meshes can greatly improve bandwidth efficiency by eschewing traditional AP-to-station topology for one where devices can directly communicate with each other. In addition, enabling mesh nodes to provide access to WiFi clients significantly extends WiFi coverage in the home. However, creating a mesh network that can dynamically and robustly route traffic over the best links to deliver satisfactory service to the home user without requiring costly setup and maintenance is quite challenging.

AirTies Mesh technology provides a solution to all of the above-mentioned problems by translating regular network devices (APs, video bridges, STBs, gateways) to Mesh Points. Each Mesh Point acts as an AP, providing a connection for wireless clients closest to it. This architecture not only dramatically increases the connectivity within the home, but it also significantly reduces the retransmission overhead inherent to the single-AP scenario, as Mesh Points can talk directly amongst themselves instead of forwarding traffic through a central AP.

Capacity Increase Throughout Home

Figure 3 depicts how the topology in the home is transformed from a star topology into a mesh when AirTies Mesh technology enables WiFi station devices to serve as Mesh Points.

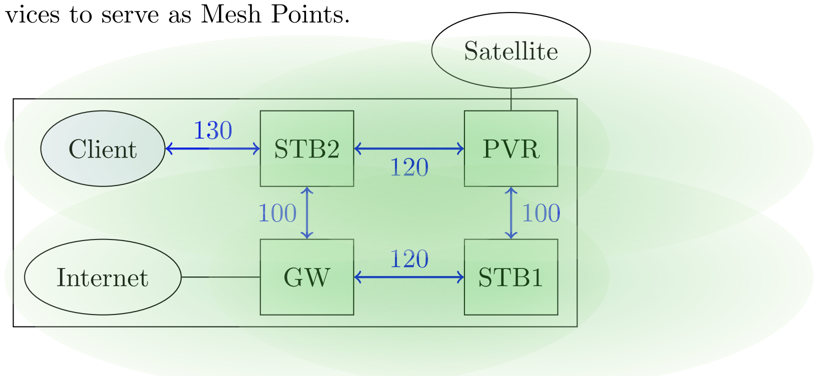


Figure 3: A home AirTies Mesh network topology. Data shared between all mesh nodes directly (without having to pass through a central AP), or via a multi-hop route that consumes less airtime than the direct route. Note that the overlapping "high throughput" zones provide much more complete coverage compared to a non-AirTies Mesh scenario.

Note the change of link capacities among STB1, STB2, and PVR compared to their respective values in Figure 2. The mesh topology enables these devices to form a direct communication link instead of being connected via the GW. The achievable capacity on the PVR-to-STB2 communication increases from 23 Mbps to 120 Mbps, about **420%**. Similar capacity increase is also seen on the connections among other non-GW devices in the home network. In addition, in the mesh network, mobile client devices can associate with the Mesh Point (that can serve as an AP) to which they have the best link at the given moment. In Figure 2, the capacity of the connection of the client device to the Internet was 30 Mbps; this value increases to about 56 Mbps in the mesh topology in Figure 3.

Easy Set-Up via AirTies Auto-Configuration Technology

With AirTies Auto-Configuration technology, AirTies Mesh Network can be easily set-up and extended. This technology has several advantages on top of WiFi Alliance's Wi-Fi Protected Setup (WPS) protocol. WPS protocol is used on AP-to-station links in order for a previously configured AP to share authentication information with a new device so that a secure link is formed between them. AirTies Auto-Configuration technology facilitates AP-to-AP configuration sharing – it enables any Mesh Point to share its configuration with a new AirTies device, upon which the new device can begin operating as a Mesh Point in the home mesh network. AirTies Auto-Configuration technology also ensures that all Mesh Points remain connected under one SSID in the home after any configuration change on any Mesh Point, and that they stay up-to-date about the status of the mesh links in order to route traffic along the best set of links.

Higher QoE

AirTies Mesh system increases the customer's Quality of Experience (QoE), most prominently for video streaming applications that have high capacity requirements. The increase in QoE is achieved via these differentiating characteristics of AirTies Mesh solution:

1. **Unified Home Network**: AirTies Mesh Points are able to also operate as APs, thereby extending the coverage area of the broadband home GW to legacy devices. Furthermore, AirTies Auto-Configuration technology allows the Mesh Points to copy the Wi-Fi credentials of the already established home network served by the GW and automatically use the same credentials in both the 2.4 and 5 GHz frequency bands (if supported) over which the Mesh Points can serve as AP. This eliminates a setup phase or avoids the possibility of hosting two separate networks in the same home.

2. **Complete coverage**: Due to its inherently scalable nature, AirTies Mesh guarantees complete high-bandwidth coverage of the house. The Mesh Points serving as AP provide coverage in all floors of the home; e.g., a tablet on the third floor of a large home can now stream video from the Internet in a home where the GW is located on the first floor.

3. **Optimal multi-hop delivery**: Via AirTies Automesh routing technology, AirTies Mesh Points find and continually update the best route to any destination device in the home. The Mesh backbone also helps to deliver data to and from mobile clients associated with the Mesh Points or connected to them via Ethernet; the data is delivered along the most robust links based on the current quality and load of the Mesh, thus remarkably increasing the video distribution performance in the home.

4. **Operating on the Best Channel**: With AirTies AutoChannel technology, AirTies Mesh devices first individually scan the spectrum to estimate channel load and then collaborate in choosing the channel with the least amount of activity heard by *all* mesh nodes rather than a single AP.

5. **Zero-second Radar avoidance**: AirTies Mesh devices all scan for radar to perform Dynamic Frequency Selection (DFS), and use the patent pending "AirTies Radar Avoidance" technology to switch to another high-power channel immediately ("zero-second") when radar activity is detected. Furthermore, the scanning for radar is performed in a seamless fashion without disrupting the QoE of the mobile devices associated with it.

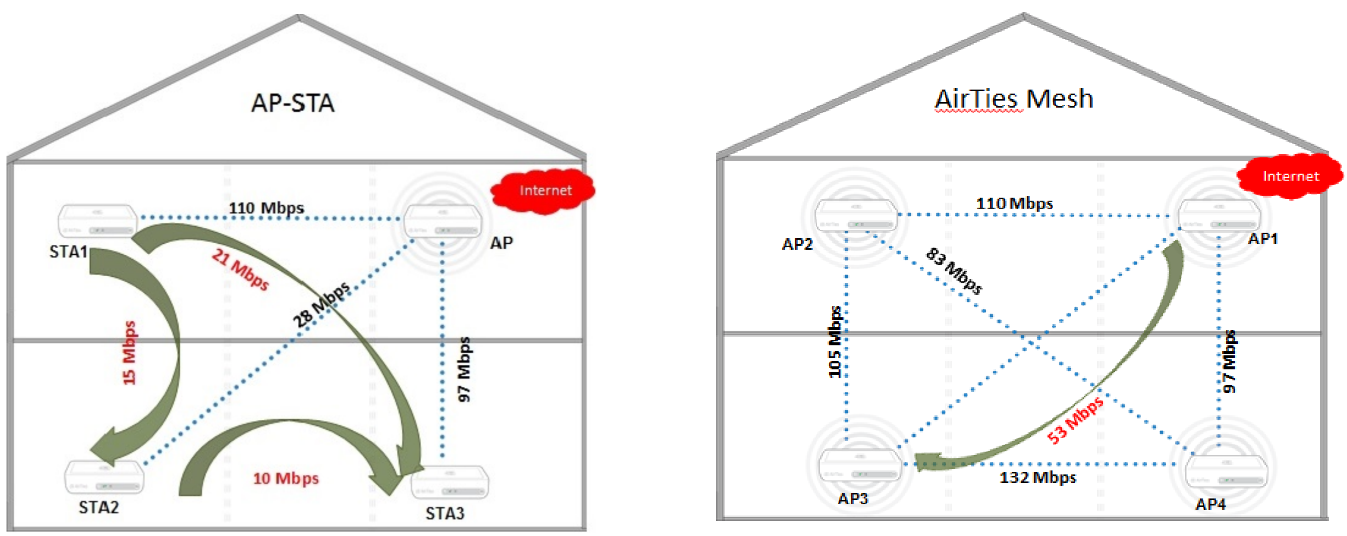
6. **Self-Healing Network**: AirTies Mesh devices cooperate to automatically and autonomously circumvent unexpected network malfunctioning. When one of the Mesh Points is turned off, or an interfering device (e.g., a walkie talkie or microwave operating at 2.4 GHz) is placed next to one of the Mesh Points impacting its reception quality, or if a Mesh Point is placed on a piece of furniture that attenuates its signals, the home users' video streaming experience may be jeopardized. AirTies Mesh Network will self-correct itself to route traffic along the current best set of links, thereby minimizing the duration of time a user's experience is interrupted for as well as minimizing the amount of performance degradation a user would experience due to the network status change. AirTies Mesh Network self-heals in a distributed fashion without need for a central management system (end user's or service providers reactive maintenance).

Remote Monitoring

The AirTies Mesh Points are equipped with the Monitoring and Configuration interface defined by the Broadband Forum, namely TR-069, which facilitates remote diagnostic monitoring and reactive remote configuration on the Mesh system from a remote entity. Operators or third-party servers can thus ensure that the network health is maintained, updates are automatically received by the Mesh Points, and configuration changes can be updated remotely without need for technician intervention.

AirTies Mesh: A Case Study

In the following, we elaborate on our observations upon performance testing in a two-floor home deployment, in terms of the network performance when AirTies Mesh technology is disabled (a legacy central-AP star topology is formed) versus when AirTies Mesh system is enabled. These measurements are carried out on four 4x4 802.11n AirTies devices, and the link capacities are measured in terms of their average TCP throughput.



(a) Star topology (single-AP) 1 (b) AirTies Mesh

Figure 4: Wireless coverage in a real-world sample home, using (a) a single-AP topology, and (b) an AirTies Mesh. Note that the AirTies Mesh link provides up to over 4x the bandwidth for point-to-point connections involving non-AP nodes in the single-AP topology.

Link Capacities in the Star Topology

Figure 4(a) depicts the star topology that is formed around the AP where each of the remaining WiFi devices connect to the AP as a station; any mobile clients in the home also associate with this AP to attain Internet access. In this figure, the capacities shown on the links that connect STA1, STA2, STA3 to the AP are the actual data rates achievable on the respective communication links (printed in black); the capacities shown on the links that connect these devices to each other are the aggregate capacities of the two-hop communication paths between these devices, going through the AP (printed in red).

This setup poses a potential coverage and video distribution problem in the two-floor home:

- Whereas both STA1 and STA3 have relatively high link capacities, STA2 is located on a far corner of the house and thus will likely have a poor connection with the AP. Primarily, even though STA2 may reach data rates necessary for delivering HD video, it might not be able to sustain these rates thereby causing intermittent frame losses and jitter in the video viewing experience. Additionally, this link will consume a great percentage of the airtime when used, leaving the remaining devices in the network to suffer due to lack of available bandwidth.

- There may be coverage holes in this home. Although STA2 has -albeit intermittent- connectivity, in the same area some mobile devices that do not have a sophisticated antenna technology or that have poorer DSPs may not be able to receive the APs signals.

- If instead of retrieving content from the Internet via the Gateway AP the STA devices were to transfer content among each other (e.g., if STA2 has a PVR cable-connected to it, STA3 is attached to a STB and the user would like to stream recorded video from the PVR), these transactions would dominate about half the available airtime, leaving little room for any mobile clients in the home to retrieve data from the Internet.

Link Capacities in AirTies Mesh

Figure 4 (b) presents the achievable data rates in the same home when AirTies Mesh system is enabled. With AirTies Mesh, each STA device becomes a Mesh Point. Note that the capacities on the direct links AP1-to-AP2 and AP1-to-AP4 in this figure are the same as those on the respective links (AP-to-STA1 and AP-to-STA3) in Figure 4 (a). The remarkable difference here compared to the legacy solution is the **up to 13-fold** capacity increase on the remaining links in the network, from 15 to 105 Mbps, from 21 to 83 Mbps, from 28 to 49 Mbps and most significantly from 10 to 132 Mbps. This is possible as AirTies Mesh technology converts AirTies stations to Mesh Points and interconnects them; each Mesh Point transfers traffic over the connection that offers the best throughput, as opposed to having to send its traffic to the AP over (potentially) a poor connection which will be forwarded to its destination – potentially over a poor connection.

AirTies Mesh setup eliminates the coverage and throughput problems that were seen in the star topology:

- The Mesh backbone constructed in the home allows AP3 (which was STA2 in Figure 4(a)) to acquire its content via a more efficient two-hop route to the Gateway AP, AP3-AP2-AP1, as opposed to using the weak link that connects them. Thus, it can attain a throughput of 53 Mbps (over the 105 Mbps and 110 Mbps links) as opposed to the 28 Mbps that was achievable with the star topology.

- As all Mesh Points also serve as APs, all mobile devices in the home can reach at least one of these APs with a good signal strength (thus with good download and upload rates). Thus, the mesh topology increases the coverage in the home remarkably for any mobile devices on both floors compared to the legacy star-topology solution, and it also provides connectivity for previously uncovered zones.

- If AP3 has a PVR attached to it, and AP4 is attached to a STB, video can now be streamed between these two devices without dominating the whole bandwidth for the remaining (on average 9, according to Table 1) devices in the home. The direct link interconnecting these devices offers a high throughput, the airtime consumed for streaming video between these devices will be a small portion of available airtime.

References

[1] ETSI EN 302 217-3 V1.3.1 2009-07, "Characteristics and requirements for point-to-point equipment and antennas"

[2] Rappaport, T. S., "Wireless Communications - Principles and Practice, 2nd Edition", *Prentice Hall*, 2002, ISBN 0130422320

[3] Courtesy of the Multimedia Research Group (MRG), `http://www.mrg.com/`.