Abstract—In this paper we address the challenge of a ubiquitous home network for new high-bandwidth applications and services such as video. We present a new concept of a hybrid coax-wireless home network using 802.11 technology. We further analyze this solution from a technical as well as other aspects and show its superiority by comparing it to other alternative solutions. With data rates of up to 54 Mbps, guaranteed QoS, security, and robust whole-home coverage, operators and service providers can deliver and distribute new bandwidth intensive services throughout the home. The usage of the popular 802.11 standard ensures many advantages such as availability and interoperability of components, low cost, and abundance of complimentary products.

1. INTRODUCTION

Wireless home networking based on the IEEE802.11 standard [1], also known as WiFi, has emerged as the preferred technology for distribution of data services within the home. With data rates of up to 11 Mbps in 802.11b and up to 54 Mbps in 802.11a/g, and with a range that covers most homes, a wireless local area network (WLAN) provides a very good solution to many home networking needs such as broadband connection sharing and file and printer sharing.

The popularity of WLAN has lead to the proliferation of systems that use 802.11b as the means to connect to the network. Notebook computers with integrated WLAN, Wireless PDAs, security cameras, printers and audio stereo equipment are just a few examples of systems that are already offered with a WLAN interface, and additional products such as PVRs, game-boxes and cellular phones are expected to include this functionality in the near future.

In this paper we address the challenge of a ubiquitous home network for new high-bandwidth applications and services. The market demand for such a network has been building for some time. Recently several proposals have been raised but none gives a good enough solution – due mainly to performance, complexity, and cost issues, or a combination of the above. Hence a ubiquitous home network for multimedia delivery is still sought.

As the popularity of WLAN grows, the utilization of the home network capacity will increase leaving less room for new high bandwidth applications. Specifically, WLAN is limited in its capability to support bandwidth intensive applications such as video distribution. Already today, WLAN capacity is marginal for video distribution within the home. Although the fastest mode of operation in 802.11g, supporting up to 54 Mbps, is sufficient for distribution of multiple standard definition television (SDTV) signals, this high-throughput mode is limited in its range and cannot be guaranteed throughout the home. Moreover, given the dynamic nature of the wireless channel with its time-varying multipath and signal fading, combined with a changing mix of stations over the network, WLAN cannot be relied upon to provide a reliable and consistent link for video distribution.

We present in this paper a new concept which allows operators and service providers to overcome the limited range and reliability of WLAN for video distribution as well as other bandwidth intensive applications. A Hybrid Coax/Wireless network which relies upon the in-home coax network to complement the wireless network and which uses 802.11g as the transmission protocol over the coax lines as well as over the air. This solution provides an economical and robust solution for distribution of video throughout the home over the in-home coax network. It uses a standard that is very robust to channel impairments such as multipath and enjoys the benefits of the economies of scale of WLAN components.

### Table 1: IEEE 802.11 Standards

<table>
<thead>
<tr>
<th>Standard</th>
<th>Layer</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11-99</td>
<td>PHY + MAC</td>
<td>Baseline, 1-2Mbps in 2.4GHz band (+IR)</td>
</tr>
<tr>
<td>802.11b</td>
<td>PHY</td>
<td>Up to 11Mbps in 2.4GHz band</td>
</tr>
<tr>
<td>802.11a</td>
<td>PHY</td>
<td>Up to 54Mbps in 5GHz band</td>
</tr>
<tr>
<td>802.11e</td>
<td>MAC</td>
<td>QoS features</td>
</tr>
<tr>
<td>802.11g</td>
<td>PHY</td>
<td>Up to 54Mbps in 2.4GHz band</td>
</tr>
<tr>
<td>802.11i</td>
<td>MAC</td>
<td>Improved security</td>
</tr>
</tbody>
</table>

By using the in-home coax network to increase the range and coverage of the wireless network, operators will be able to offer reliable video distribution, as well as other services, throughout the home with guaranteed high capacity coverage at every point in the home while enjoying all the advantages of 802.11 standards, including QoS, security and low cost.

In section 2 we discuss the applications and requirements for the multimedia home network. In section 3 the general concept of our proposed solution is outlined. Section 4 discusses the network topology and products of our solution, followed by technical considerations given in section 5. In section 6 we compare our solution to other alternative solutions, and conclude with a summary given in section 7.
2. APPLICATIONS AND REQUIREMENTS

Market demand for a multimedia-capable broadband home network has been building for some time. Some driving applications that motivate the implementation of the multimedia home network are IP-Data, Video Distribution, Audio Distribution, Security and Monitoring and Voice over IP (VoIP).

To answer the market demand for the above applications, the multimedia home network needs to meet the following requirements: “No New Wires”, High Throughput (greater than 20Mbps), Quality of Service (QOS), Whole-home coverage, Robust operation, Simple Installation, Coexistence with other home appliances, Secure connections and Low cost.

3. GENERAL CONCEPT

We propose a home network based on 802.11 transmissions both over the air and over coax (throughout this paper the term “802.11” will refer to all 802.11 based standards including all the various extensions, 802.11 a,b,g,e and i). Figure 1 gives a basic block diagram of such a hybrid coax -wireless 802.11 network. The network includes an Access Point (AP) with an antenna for wireless 802.11 home networking, as well as a coax connection. The network also includes three stations (STA): one connected to the network through a coax line and two STAs connected through a wireless link. On one of the nodes of the in-home coax network there is an extender/repeater that serves as a coax to wireless bridge and extends the coverage of the wireless network. Every packet can be transmitted either over the air or over coax or both over the air and over coax. Consequently, each data packet can reach its destination through one of three signal paths: A direct wireless connection using the antenna connected to the AP; A combination of coax line until the repeater, and then wirelessly to the wireless station; Over the coax cable alone.

All transmissions, both over the air and over the coax cable are in the 2.4 GHz frequency band (used by 802.11 b and g).

Figure 1: Block diagram of a hybrid coax-wireless home network

In most homes the propagation loss of 802.11b/g in the 2.4 GHz frequency band is much lower over the coax than over the air especially when accounting for obstructions to the wireless signals such as walls. Therefore, the coax line allows extending the reach and expanding the coverage of the network by bypassing a high-loss and constantly changing wireless path with a low-loss and deterministic coax path or a hybrid coax/wireless path. The all-coax path between the AP and stations on the coax network is particularly of high quality and robustness, allowing reliable operation at the highest possible data rate of 802.11g - 54 Mbps.

Figure 2 illustrates an example of such a network in a typical home, with broadband access over cable. The home in this example uses 802.11g for data and video distribution. The Digital Set-Top-Box (STB) on the first floor serves as the residential gateway with an embedded DOCSIS™ cable modem and an 802.11g AP. The notebook computer in the home office on the first floor is connected to the STB/RG via wireless 802.11g link. The desktop in the bedroom on the second floor is too far to wirelessly communicate with the STB at high enough data rate. Instead it communicates either over coax (if there is a coax connection nearby) or wirelessly to the repeater on the second floor and then over coax to the gateway. Utilizing the repeater on the second floor, the notebook computer, when moved to the second floor, communicates wirelessly to the repeater and then over coax to the gateway. This enables maintaining the highest possible data rate throughout the home.

Figure 2: A hybrid coax-wireless home network in a typical home

The main STB on the first floor communicates with the secondary STB on the second floor over coax, again maintaining the highest possible data rate, needed for enabling video distribution throughout the home and other services described in the previous section such as sharing of recorded material on PVRs, allowing access from all STBs to email, Internet etc. The STB with AP can become the home media center with stored video and audio, with other scaled-down (thin) STBs having access to this information through the coax network. Using this technology allows all STBs to have access to data services and computer resources in the home such as printers, scanners, cameras etc.

It is important to note that the wireless only solution might have been sufficient for data service alone, however higher throughputs of up to 54 Mbps that are needed for video distribution require the coax link between the STBs.

The QoS capabilities of 802.11e will ensure efficient use of the shared medium, as well as guarantee allocation of bandwidth and limit latency for services requiring QoS. For homes with broadband access via cable, CableHome™ functions implemented in the STBs will facilitate the management of the home network, but this technology works alongside with any other access technologies – DSL, Satellite, etc.
Overall, the combination of a high capacity coax channel and 802.11e assures operators that bandwidth intensive services such as video distribution can be delivered reliably and consistently between stations on the coax network.

4. NETWORK TOPOLOGY AND PRODUCTS

The hybrid coax-wireless home network using 802.11 technology consists of two types of devices, categorized based on their role in the network, and a third type that is a hybrid between the two. These are: Server / Access Point (AP), Client / Station (STA), and Wireless extender.

In terms of products we envision two segments, as depicted in Figure 3: Data segment products – For example AP or RG with 802.11 over coax support (this can be done also by upgrading an existing AP or RG), Wireless Extender with 802.11 over coax support, Desktop Station with 802.11 over coax support. Video segment products – This segment is relevant regardless of the access technology (e.g. Cable, DSL, etc.). Products include for example Primary PVR/DVD/STB with 802.11 over coax support, Thin STB with 802.11 over coax support, Desktop Station with 802.11 over coax support serving as a second multimedia source.

One possibility is that these two segments will be unified into one line of products, serving both data and multimedia needs. Another option is that they will remain separate, with distinct devices in each segment, and possibly even two separate networks supporting the two segments (using 802.11 over coax this can be done for example by utilizing more than one channel).

In the following we discuss the three types of devices. We then discuss some complimentary product, namely the matching element and the upgrade kit.

4.1. SERVER / ACCESS POINT (AP)

This type of devices serves as an access point of the home network to the WAN on the one hand, and as the server of the home-network on the other hand. These two functions can be integrated in one device, or it is also possible that the connection of the AP to the broadband access will be through another device – for example an AP that connects via Ethernet to the home cable modem or DSL modem, which in turn is connected to the broadband access.

A block diagram of the PVR/DVD/STB with 802.11 over coax support and wireless AP functionality is given in Figure 4. Notice that the wireless AP functionality is optional and may be removed in order to reduce cost. Similarly an AP that is part of an RG unit can have 802.11 over coax as well as wireless support. An AP-only device is of course a subset of this RG. Notice that the above devices can be unified into one unit that is the center of both data and video for the home.

The AP that resides in these devices is a standard 802.11b/g AP. One position of the antenna switch is used for the coax transmissions whereas the other may be used for wireless transmissions. The communication of the 802.11 device with other internal unit is done for using an internal bus between the AP and the other module. Communication with other 802.11 devices in its network is done using 802.11 packets. Based on the senders and desired recipients, packets are sent and received either over the coax by turning the antenna switch to one position, or over the air by turning it to the other position.

![Figure 3: Product Offering](image)

**Figure 3: Product Offering**

![Figure 4: STB/DVD/PVR with 802.11 over coax support](image)

**Figure 4: STB/DVD/PVR with 802.11 over coax support**

The AP can be configured to operate either wirelessly or over coax. With some additions it can operate simultaneously over the air and over coax. As can be seen, no system changes are needed for a standard 802.11g AP. The only addition needed is the matching splitter – a passive device that is discussed in detail below.

4.2. CLIENT / STATION (STA)

Multiple such devices may reside in various locations throughout the home, and serve as clients in the home network. They communicate with the AP either wirelessly or over coax.

A block diagram of a Thin STB with 802.11 over coax support and wireless STA functionality is given in Figure 5.

The thin STB may consist of a video codec, and a processor that can serve as a host for the 802.11 STA. Figure 5 also gives a block diagram of a desktop Station with 802.11 over coax support and wireless STA functionality. Using this desktop STA, any desktop can become a second video source that enables viewing data from the desktop (e.g. movie clips, DSC photos, etc.) on any of the TV’s connected to the hybrid coax-wireless network.

The STA that resides in these devices is a standard 802.11b/g STA. One position of the antenna switch is used for the coax transmissions whereas the other may be used for wireless transmissions. The communication of the 802.11 device with other internal units is done using an internal bus. Communication with other 802.11 devices in its network is done using 802.11 packets. Based on the mode of operation, packets are sent and received either over the coax by turning
the antenna switch to one position, or over the air by turning it to the other position.

The STA can be configured to operate either wirelessly or over coax. With some additions it can operate simultaneously over the air and over coax. As can be seen, no system changes are needed for a standard 802.11g STA. The only addition needed is the matching splitter – a passive device that is discussed in detail below.

4.3. WIRELESS EXTENDER (WEX)

This hybrid device serves as a client in the home network communicating with the AP over coax, and extends the reach of the network via wireless communication to other (e.g. remote) devices.

4.4. MATCHING SPLITTER AND UPGRADE KIT

The matching splitter is the only additional hardware needed to enable a device supporting 802.11 to support 802.11 over coax as well. A block diagram of the matching splitter is given in Figure 6. This splitter can be internal or external.

5. TECHNICAL CONSIDERATIONS

Although all the components of the in-home coax network were designed for signals below 900 MHz, the 802.11 signal is robust enough to operate smoothly over this network in its native 2.4 GHz band. In this section we consider the robustness of this technology and address the issues of attenuation and reflections due to the in home coax network.

5.1. ATTENUATION AND LINK BUDGET

Table 2 gives the transmission power, noise power and SNR needed for 802.11g to operate at different modes. Based on this table, it is evident that the link budget, for a sufficient TCP throughput of over 15Mbps, is 90-100 dB.

![Figure 5: Thin STB and Desktop STA with 802.11 over coax support and wireless STA functionality](image)

![Figure 6: Matching Splitter](image)

![Figure 7: Upgraded AP](image)

![Figure 8: TCP Throughput vs. Attenuation for 802.11g over Coax](image)

Table 2: 802.11g parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx Power</td>
<td>Up to 20dBm</td>
</tr>
<tr>
<td>Noise Power</td>
<td>-94dBm</td>
</tr>
<tr>
<td>SNR needed @54Mbps</td>
<td>~25dB</td>
</tr>
<tr>
<td>SNR needed @11Mbps</td>
<td>~10dB</td>
</tr>
</tbody>
</table>

![Table 2: 802.11g parameters](image)
Figure 8 gives the measured TCP throughput between two notebook PC’s with 802.11g cards communicating over coax, as a function of the attenuation between them. This attenuation results from different combinations of cables and splitters that were put between the laptops. As expected, the graph shows that sufficient TCP throughput of over 15Mbps can be achieved even with attenuation of 90-100dB between the laptops.

Extensive work has been done to characterize the in home coax network. Since many components that are commonly used in the home coax network are unspecified in the 2.4GHz band, these components were measured to create a reliable model of the in home coax network in the 2.4GHz band. These components include various types of coax cables, numerous splitters (including 2, 3, 4, 6, 8 way splitters) and other components that are found in the home coax network.

Table 3 and Figure 9 summarize some results of this work.

Table 3: Characteristics of the in home coax network

| Splitter Attenuation – Insertion | <30dB |
| Splitter Attenuation – Isolation | <30dB |
| Cable Attenuation | 0.5-1dB/m |
| Matching splitter Attenuation | 2*1dB |

Figure 9: Splitter parameter histograms

Based on the robustness of the 802.11 technology, and the results of the measured in home coax network, with typical attenuation of 0.5-1 dB per meter cable and 20-30 dB attenuation of common splitters (measured between splitter outputs and between input to output at 2.4 GHz), the in-home coax path is still less demanding than even good wireless channels. Since existing 802.11b/g systems can tolerate 90-100 dB of attenuation between transmitter and receiver while still maintaining high throughput, this allows a link attenuation budget that can accommodate hundreds of feet of coax cable and several splitters.

5.2. Reflections

The hybrid coax-wireless network also introduces multipath due to unterminated cables and splitters. Figure 10 depicts an exemplary case of this phenomenon. However, 802.11 devices are designed to mitigate even severe cases of multipath given the many reflections and signal paths in a typical wireless environment. The robustness of the 802.11 devices, and the typical reflections in the in-home coax network are summarized in Table 1. This shows clearly that 802.11 devices can mitigate even severe cases of multipath resulting from the in-home coax network, again indicating the robustness of the proposed technology.

Table 4: Reflections in a hybrid coax-wireless network

| Reflections 15m | 125nS |
| Reflections 30m | 250nS |
| Typical 802.11 supports | 0dBc echo up to >500nS |

Figure 10: Multipath in a hybrid coax-wireless network

6. COMPARISON TO ALTERNATIVE SOLUTIONS

Various solutions addressing the problem of multimedia distribution within the home have been proposed to operators and service providers. Below is a comparison of these solutions to the one proposed in this paper. This comparison is summarized in Table 5:

Table 5: Comparison to alternative solutions

<table>
<thead>
<tr>
<th>802.11 over coax</th>
<th>WiFi 802.11</th>
<th>HPNA 2.0 over coax</th>
<th>Proprietary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market Acceptance</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Supported by Standards</td>
<td>High</td>
<td>High</td>
<td>Yes</td>
</tr>
<tr>
<td>Performance, Quality</td>
<td>54+ Mbps, Robust!</td>
<td>54+ Mbps, Quality?</td>
<td>16-32 Mbps</td>
</tr>
<tr>
<td>Coverage</td>
<td>Ubiquitous</td>
<td>Ubiquitous</td>
<td>Coax, Phoneline</td>
</tr>
<tr>
<td>Coexistence with Cable services</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Complimentary Products</td>
<td>Many</td>
<td>Many</td>
<td>Very Few</td>
</tr>
<tr>
<td>Incremental Cost</td>
<td>Low (same WiFi chipset)</td>
<td>Low</td>
<td>High (additional chipset)</td>
</tr>
</tbody>
</table>

6.1. ANALOG DISTRIBUTION

Analog distribution provides a simple solution for video distribution within the home, with the distinct advantage of not requiring a separate converter box to decode the upconverted video signal. However, this solution is very limited both in functionality and quality. Data delivery, including remote control data (e.g. IR control), will require a separate medium and additional components. In addition, the quality of the picture can be poor due to micro-reflections in the coax
While providing in most cases complete home coverage at rates that support the sharing of the broadband connection for data services throughout the house, it may be insufficient for multimedia distribution. The high throughput modes of operation are the ones most susceptible to wireless path loss and multipath, and coverage for modes that can support video distribution may not be complete. To expand the reach of the network, wireless repeaters can be used. Repeaters indeed improve the coverage (at the expense of additional spectrum usage), however without careful planning complete coverage is still not guaranteed, and this solution is less robust and more expensive than the hybrid coax/wireless solution proposed in this paper.

6.3. **HPNA and HPNA over cable**

HPNA 2.0 has not been successful in the market as a home networking technology. Even though its data rates are sufficient for high-speed data service, it has lost market share to the much more popular wireless alternatives. Coverage in many homes is incomplete due to locations of phone outlets, and the use of the phone wire for home networking is not as intuitive to many users as wireless. In fact, as the number of silicon and system vendors developing 802.11 based solutions has increased dramatically, the number of silicon and system vendors developing HPNA based products has decreased, making this technology even less attractive due to lack of competition.

For multimedia applications HPNA 2.0 is not suited at all. Practical data rates are not sufficient for video distribution, and QoS mechanisms in the specification are minimal, leading to inefficient usage of the shared medium and not allowing operators to guarantee QoS for revenue services. The next generation standard HPNA 3.0 may address this problem, however it still has many of the other problems that made HPNA 2.0 so unattractive as a home networking technology.

There have also been proposals for using HPNA 2.0 over cable in a similar way that this paper proposes for 802.11. However, HPNA over cable interferes with STB communication (by operating at the same frequencies) and with cable upstream transmissions (again, due to overlapping spectrum). In addition, unlike the high rate modes of 802.11g/a with the QoS option, HPNA 2.0 is not capable of distributing multiple MPEG streams over the coax cable due to insufficient throughput and lack of QoS. These issues coupled with the lack of HPNA 2.0 silicon vendors, make this solution essentially a proprietary solution.

Moreover, to bridge between the coax and phone network, there needs to be at least one point in the house where coax and phone lines meet. Since in many homes coax and phone outlets are on opposite sides of the rooms, bridging the two networks may not be as simple as in the wireless case.

Finally, given the popularity of wireless home networking, it is likely that wireless home networking may still be required at the AP. Wireless handheld devices, and corporate computers equipped with a wireless LAN interface, as well as other devices not near a phone or coax outlet, cannot be served by a HPNA coax/phone-line solution. Complementing HPNA with 802.11 will lead to an inefficient, redundant solution compared to the 802.11 coax/wireless solution.

6.4. **Dedicated coax transceiver (’HomeCNA’)**

Several companies have proposed coax based home networking solutions that use a non-standard transmission protocol. Indeed, an optimized protocol for delivering multimedia over coax can provide a good technical solution, but it is less likely to be adopted than a solution that is already based on an existing standard, especially one so popular as 802.11. Developing a new dedicated standard and new components for cable home networking is a long and expensive proposition. Chances of multiple vendors signing up for such an effort are slim. Any technical advantages that such an approach may have over using 802.11 as the transmission protocol are by far outweighed by the advantages of relying on existing, proven standards and, more importantly, existing 802.11 silicon.

Even if such an approach is adopted, STBs will still require another home networking technology, in addition to the coax networking technology (presumably wireless), to connect to devices that are not near a coax outlet. This is an inefficient (and costly) solution compared to a single 802.11 interface in the STB that transmits both over the air and over the coax.

While dedicated coax home-networking solutions may claim a higher throughput than those supported today by 802.11 (100 Mbps and above compared to 54 Mbps), it is worth noting that 802.11 has a dedicated study group looking at higher rate extensions to 802.11 that will provide even greater capacity for bandwidth intensive applications and services.

7. **SUMMARY**

We introduced a hybrid coax-wireless home network for bandwidth intensive multimedia applications and services using existing 802.11 standards and components. With data rates of up to 54 Mbps, guaranteed QoS, security and complete home coverage, operators and service providers can now have a solution that will allow them to deliver and distribute reliably throughout the home services that require both high capacity and guaranteed QoS such as video.

By using the existing 802.11 standard, operators ensure the availability and interoperability of components from multiple vendors and take advantage of the competition and high volume in the 802.11 market space leading to a low cost, low risk solution.

The popularity of 802.11 both in the home and enterprise space, and the many 802.11 based products such as notebooks with integrated wireless, wireless enabled PDAs, and 802.11b security cameras, will also facilitate wide adoption of this hybrid coax-wireless 802.11 home multimedia network.

8. **REFERENCES**