The State of Home Networking
Home Networking from B(luetooth) to Z(igBee)
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Introduction

The past half-decade has seen a tremendous growth in the practical ability and usage for networking devices within the home. The home environment is not an easy one, with multiple product/use spaces, and data throughput requirements that run over 9 orders of magnitude (figure 1). In the computing environment, the existence of more than one computer provides a logical reason to create a network, so long as it's more cost-effective and functional than the "sneaker-net" approach, where needed data is hand-carried between computers on disks or FLASH memory devices. Consumer electronics (CE) devices in the home have traditionally relied upon the sneaker-net approach – a DVD or VHS tape is a physical device, and (currently) must be transported manually between devices in the home in order to enjoy the content. Upgrading this network goes well beyond the technical aspects of network construction and usage, since the content owners, providers and other parts of the delivery chain are deeply concerned over content piracy. Finally, the third network that was until recently strictly manual was the home control, monitoring, energy management, convenience and security environment. Determining energy usage, cost for that usage, optimizing the home's environment while minimizing operating cost was a very after-the-fact analysis, and one that now has become of great importance in this era of high energy costs, heightened awareness of impact to our global environment, and dwindling energy reserves.

Figure 1. Radically Different Domains in the Home

While networking methods cannot solve the political and legal issues around moving data electronically between devices in the home, the networking technologies developed and fielded over the last several years has made it possible to make robust and reliable networks supporting data rates from less than a bit per second (control and sensing) to well over 1 Gbps (live, uncompressed video for computer displays), an astounding range of over 9 orders of magnitude. With this kind of data rate range, and the tremendous variations in requirements for quality of

service, latency, jitter, and differences in usage (retrieving sensor information, transferring data files, streaming high quality, high-definition audio and video, it's no wonder that one network technology cannot do it all.

Wired and Wireless – Two Sides of the Same Coin

There are plenty of networking technologies available to throw at the problem: the two most used and "content-agnostic" are the wired and wireless forms of Ethernet. The wired form, IEEE802.3, is incredibly flexible, and the costs for infrastructure (wiring, switches, hubs, routers) very reasonable. The biggest challenge is the routing of the wire itself – this can mean holes in floors, walls, crawling around under the house, or in the attic, snaking cables through difficult spots, but once it's done that cable can deliver reliably tens to hundreds of Mbps. In many cases though, the cable routing may be the most expensive part of the network installation, exceeding even the cost of the rest of the hardware. In other cases, it may be impractical or prohibitive, especially in the case of homes without subfloor or attic crawl spaces, that contain materials that are toxic if disturbed (like asbestos), walls made of stone or concrete, or designated historical buildings where modification may be severely restricted.

Enter wireless Ethernet or IEEE 802.11 in its many flavors, with products certified for interoperability by the Wi-Fi Alliance. Wi-Fi is the wireless analog to wired Ethernet – while not as robust or reliable as "good-old" copper wire, it is substantially easier to install and has adequate range and performance in most operating environments. Introduced toward the end of the 90's, in 2006 it exceeded for the first time a total of 100 million units sold in a single year. Instantaneous data rates over the air range from 1Mbps to at least 100Mbps, with a solid roadmap to hundreds of Mbps as the 802.11n amendment is ratified and products built. Instantaneous rates are somewhat misleading, except as a rough comparison between different wireless techniques.

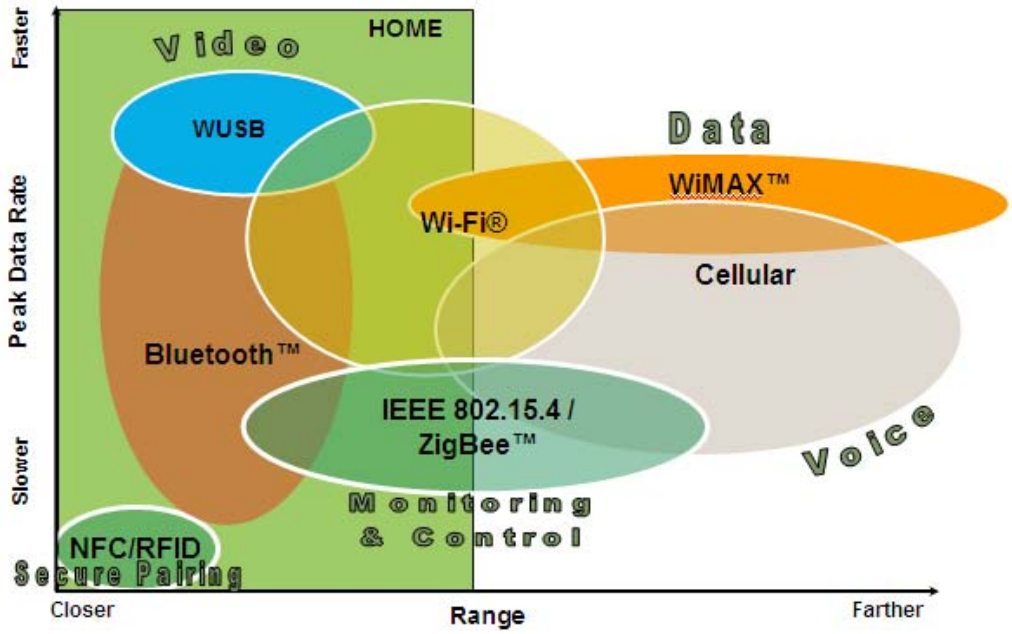

Figure 2. Wireless Technologies for the Home

The wireless universe (Figure 2) is a very different place than the wired space. On the wire, all of the stations connected can know within the propagation time down the wire whether some other station has already accessed the wire. There's no hidden transmitters, no propagation issues that prevent one network controller from hearing another network controller on the same wire. In the wireless space, suddenly there's a chance that Station A, in the living room, which can hear the access point AP just fine, may not be able to hear Station B in the bedroom. Thus, if Station B is

already transmitting a packet to the AP, Station A has no way of knowing that and may decide to attempt to transmit a packet of its own. For the AP, Station A's transmission may corrupt the packet being received from B at that moment, causing the loss of that packet and forcing a retry. Also, since the AP was in the middle of receiving Station B's packet when A's packet began, it isn't able to resync to A in time, so A's packet is lost also. Once it's all over, both packets are lost, and both Stations A and B must go through a clear channel assessment procedure which includes a random delay before attempting to transmit again. This collision, delay, and retry, while a robust mechanism and important for maintaining the ability of the radio channel to function properly, causes a significant reduction in the overall capacity of the channel to carry information. Thus, the 54Mbps instantaneous transmission rate advertised by IEEE 802.11g/a is really more like 20Mbps when there's only two devices on the channel, the Station and the AP, and when they're in close proximity to one another. Add one or two more active devices and the real throughput can easily drop to under half that. But, if the system is capable of managing with only 5Mbps average throughput, and there's 10 Mbps available, the system can work well. And with 802.11n coming up, the potential for real throughputs of 20-60Mbps are practical given the ultra high instantaneous capacity of the .n radio. That's enough to carry a couple of high-definition video channels, with plenty of extra bandwidth available for internet surfing, digital telephone, and other uses.

While the flavors of wired and wireless Ethernet are probably most common in the home, there are other ways to connect points within the home. Other "wired" methods include digital communication over the AC power lines – HomePlug technology, developed by the HomePlug Powerline Alliance, uses an OFDM transceiver with multiple carriers between 2 and 28 MHz to transport information over the house's copper wiring. OFDM technology and the use of many carriers, each containing a portion of the overall data stream, is resilient to the poor propagation and high noise environment within the home; as a result, HomePlug A/V (the current best version) can provide instantaneous data rates of approximately 200Mbps. Once the protocol overhead is subtracted, this still provides a best case capacity of about 100Mbps, and without many of the issues of hidden transmitters. To date, HomePlug has not been nearly the success that Wi-Fi has demonstrated.

HomePNA is another "wired" networking technology, this one similar to powerline communication but using the phone lines that are generally available at several spots within the house. Newer versions of HomePNA can also take advantage of distribution over the coaxial cable networks that are becoming more common in many North American homes. With data rates to over 300Mbps, and the ability to provide good quality of service, important for accurate and timely delivery of audio and video, HomePNA seems like a technology that can solve many of the networking problems within the home, using copper that's already installed.

There are some other similar technologies out there that take advantage of the coaxial system within many homes – the Multimedia over Coax Alliance (MOCA) uses a proprietary OFDM transceiver to deliver data at rates of approximately 100Mbps, and the High Definition Audio Video Network Alliance (HANA) is working on, among other things, the use of Ultra Wideband over coax to deliver true IEEE1394A rates (400Mbps) over coax, complete with the native isochronous ability of IEEE 1394, which was designed to manage streaming video and audio.

Low(er)-Rate Networks

When someone mentions home networks, it's almost inevitably in reference to high data rate systems that are connected to permanent sources like the AC line or large batteries like those found in the typical notebook computer. However, with the advent of the IEEE 802.15.4 low-rate wireless standard and the ZigBee networking protocol, the consumer may someday refer to their home control network, or home security/safety network, which will be a different thing from that high-rate network. Built for devices that may get all their power from a small lithium battery or a couple of AAA alkaline cells, IEEE 802.15.4 is well suited for devices that may be something as simple as a peel-n'-stick light switch, door security sensor, or thermostat, where the battery is shipped with the product. Once on the wall, the device's average power consumption is less than the self-discharge rate of the battery, meaning that the battery will die due to old age before being

depleted enough to require replacement. This can be from 5 to 7 years for alkaline battery technology, and 10 or more years when lithium cells are used. At lifetimes as long as these, there's a good chance the consumer will have decided to change their home's décor, repaint, and replace all the light switches and thermostats with new ones before the original switches' batteries have failed.

IEEE 802.15.4 and ZigBee

Low rate networks have to be robust and reliable when used in security, safety, or even convenience applications. IEEE 802.15.4 has many features designed in to support reliable performance with a broad range of "knobs" to tweak the performance for the specific application. ZigBee networking technology expands on the strengths of the IEEE 802.15.4 radio (Figure 3) and adds a native mesh networking topology and functionality to the already strong radio functionality. Mesh networking means that a message between Station A (light switch) and Station B (load control) may have more than one path available to transfer the message successfully. Since the radio channel is not perfect (for all the reasons mentioned earlier), the most successful path between source and destination may not always be the most direct. The path between A and B may include large, moveable objects that can reflect, absorb, or otherwise impede radio signals. People are terrific RF absorbers, and a herd of people milling around in the kitchen can change the propagation characteristics of signals that must pass through that kitchen. Station A might be in the living room, while B is in a hall closet. Often, the direct path is perfectly fine, and when the button at A is pushed, the light attached to the load controller at B turns on. However, when someone opens the refrigerator door, that large metal door could cause a degradation in the link performance between A and B, and make it far less reliable. So, when the button at A is pushed, it tries the direct path first; if that doesn't work, it attempts other, less direct paths that may end up having superior stability and performance. So long as all of this rerouting takes place on the order of 100-200 milliseconds or less, the delay between the button push and the light turning on is acceptable.

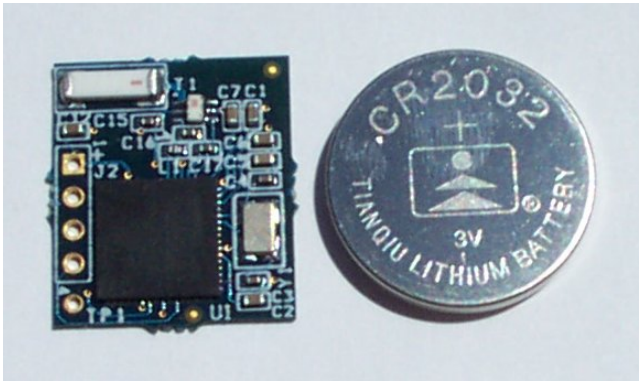

Figure 3. Typical IEEE 802.15.4/ZigBee Radio (courtesy Freescale Semiconductor)

With ZigBee networking on the IEEE 802.15.4 radio, the typical two-way single-hop transmission time from beginning of outbound message ("turn on the porch light") to return receipt of the message acknowledgement ("message received successfully") can be as short as 3-4 milliseconds. So even if it takes a few retries to deliver that message, it's hard to imagine a situation where the total delay from button push to the light coming on can exceed a few dozen milliseconds, and even harder to imagine the message not getting through in a hundred or two milliseconds. And even when the home is large enough that it takes a couple of hops to make it from one side to the other (IEEE 802.15.4 radio ranges average 20-70m in typical North American home construction), there's plenty of time to get the message from source to destination.

While ZigBee technology, developed by the ZigBee Alliance, has only recently started to find its way into end products, 2007 promises to be a strong year for the adoption of the technology (as well as the underlying IEEE 802.15.4 radio technology) in new products and application spaces.

Bluetooth

But IEEE 802.15.4 isn't the only short-range wireless technology. What about Bluetooth? What about Wibree? Bluetooth is the world's most successful (in terms of market volume) short-range wireless technology. In 2007, analysts estimate that each week between 5 and 10 million Bluetooth radio chips will ship. While most of these are going into cellular handsets or headsets for the mobile phone, an increasing number are finding their way into other accessory devices, or PCs, PDAs, personal navigation devices, portable media players, hands-free devices for automobiles, or other applications. And with the release of the Bluetooth 3.0 specification with the "high-rate" alternate physical layer, the potential for Bluetooth to expand its reach into the CE space grows stronger. While the 30-50Mbps expected from the first generation of BT3.0 devices is barely enough for high quality streaming media transfer, it's a good step toward being able to bring an alternate wireless method to bear on networking those DVRs, TVs, DVD players, and stereo receivers. Whether the technology promised will be timely, power effective, provide sufficient range or reliability remains a big question, but with the success of Bluetooth technology to date there's a good chance that Bluetooth will play a significant role in the future of wireless networking in one's personal space, whether that's in the automobile or in the home.

Wibree

Wibree, announced late last year by Nokia, is a simplified version of Bluetooth optimized for battery life. Bluetooth uses Frequency Hopping Spread Spectrum (FHSS) technology, good for improving path robustness between source and destination. However, at 1600 channel changes per second, if the transmitter and receiver are not precisely synchronized with one another, little or no information can be transferred. That synchronization means that both ends of the circuit need to know what channel the other is currently on, and what channel will be next. Both devices keep their transmitters and receivers on intermittently to allow the other to remain in step. This half-awake mode draws significant power. The Bluetooth SIG was willing to accept this since their primary goal early on was to be parasitic to the regularly recharged battery of a host device, like a cell phone or notebook computer. And while the problem remains for the Bluetooth headset that is paired to that phone, it's a simple matter to recharge the headset when it's time to recharge the phone. But, Bluetooth is not optimized for that wireless keyboard or mouse on the PC, hence the value for Wibree.

Wibree is based to a great extent on a non-hopping Bluetooth radio variant. No hopping means the ability to sleep deeply when communications are not necessary. For the wireless keyboard on the desktop, if there's no one typing at that moment, why stay awake? If upon a key strike, the system can wake up and transmit its keystroke value in 10-30 milliseconds for the first key and less time for each keystroke following, then the needs of the typical computer user are well met. In addition, since Wibree is based upon the Bluetooth radio, a Bluetooth radio that can be "dumbed down" can speak to Wibree radios. For next generation Bluetooth radios available later this year or early 2008, this ability could be as simple as a change in firmware, downloaded over the cellular network. Now, that phone could act as a projector controller, a wireless mouse, or similar function. Wibree is not a competition to Bluetooth, but an extension of capabilities into a space for which Bluetooth was not well suited.

RFID

Finally, there's one significant other short-range wireless technology that has already found its way into homes, generally through childrens' toys (ever wonder how that doll "recognizes" when the little girl holds the toy apple to the doll's mouth?) but also in sometimes less comfortable instances as tracking tags for products, clothing, or even your passport. RFID technology is mature, inexpensive, and growing in utility and pervasiveness. Once restricted to supply chain management, its ultra-low cost and simplicity have found it niches in toys, e-payment systems at gas stations, convenience stores, and supermarkets, as well as the basis of the modern collection

system for toll highways. The readers (the other end of the circuit), while significantly more expensive and complex, have also improved to the point that industry groups like the Near Field Communications (NFC) Forum are working with the cellular handset and cellular/banking infrastructure industries to make every cell phone capable of being both the tag (for instances where reader infrastructure is already available) and the reader, when the only secure network backhaul is the cellular network itself. The technology employed in the latter means that an ad in the train terminal for a book or product can become the actual point of sale for that product, where the consumer touches the ad with their phone, presses the “buy me” button on the phone, and a day or two later finds the product or book on their doorstep.

The future is bright for both low- and high-data rate network technologies, wired and wireless, with the mobility provided by wireless of especially high value going forward.

Bridging Between Networks

There will be different networks all living together in the home, due in no small part to the significantly different requirements placed on those networks by their client devices. It’s not practical to build a single network that provides adequate performance for all the possible devices over that billion-fold data rate range. This is like all roads replaced with freeways – fine for some purposes, ideal for others, but where do you ride the bicycle? One size does not fit all, and especially in data networks. Interchange from one network to another is a critical function, and one that requires intelligent devices that understand the characteristics of both networks and can speak in a common language. While the computer may have a ZigBee radio directly attached, so that the home can be monitored by the computer, or even configured via a user interface that resides on the computer, there may be parts of the home (or extended parts of the property if you live on a cattle ranch) where ZigBee doesn’t reach directly – for those extended portions of the network the ZigBee protocol may need to be transported over IP to a IP to ZigBee bridge out by the barn, or down in the wine cellar. The same issues hold even more true for high speed connectivity for media over the property – Wi-Fi performance may vary widely due to propagation issues, so a wireless-to-wired bridge, with the wired component using wired Ethernet or HomePlug, may be necessary to maintain a robust and reliable network.

Now That My Network’s Installed, Where’s My Content?

While it’s not an issue for a ZigBee network, any high rate network that proposes to handle in some way protected content must provide sufficient security mechanisms to ensure that the data transported over that network cannot be compromised. This is a tall order, and not adequately solved today. The internet and Ethernet in general were able to grow up in a time when content piracy was less of a problem or at least less widely recognized as a problem. Today, we have a ubiquitous IP transport network that can move any IP-based content from Tucson to Timbuktu in seconds. This very success and strength of the Internet is one of the great challenges to the appropriate control of content owners’ rights to control access to their content. That very same connectivity that allows your email and photos from your African safari to get back to your friend’s home in Tucson can also provide an illegal distribution pipeline for a digitized version of the latest Hollywood blockbuster. The threat of denial of rightful income for the content owner has kept the consumer electronics realm separated from the IP universe, and even one CE device from the other. Groups like DLNA (Digital Living Network Alliance) and HANA, among others, are working with content owners and service providers to figure out ways that your licensed content is free to move wherever you want within your devices and your personally generated content as well as restriction-free content is free to move anywhere you want at any time.

Conclusion

Not all homes are created equally – whether larger or smaller, built from straw, brick or steel, both wired and wireless network components may be part of the solution for each. For home control and monitoring, IEEE802.15.4 wireless with ZigBee network technology is the likely candidate for

cost-effective, battery-efficient networking of lighting, home automation, HVAC, security, safety, yard and garden functionality in the residential space. The combination of these international, open standards, manufactured by most of the top-10 silicon vendors, coupled with a rich developer ecosystem means strong availability, excellent price competition, and significant enhancements as a result of competitive differentiation. For higher rate data and media networks, Wi-Fi and its offspring has tremendous traction and market presence that makes it a formidable target to beat for the other network technologies on the drawing boards. The practical, on-the-shelf products available today and over the next few years provide the consumer a variety of broadly optimized, industry-supported networking technologies that will drive the home of the next decade.