Wireless Networking Choices for the Broadband Internet Home

The clear choice is HomeRF and what happens in other segments of the wireless connectivity market is of secondary importance at best.

Executive Summary

This white paper examines three candidate wireless networking standards, HomeRF, Bluetooth and IEEE802.11, against the needs of service providers and consumers for the Broadband Internet home. The clear choice for this specific application based upon technical merit is shown here to be HomeRF. Only HomeRF provides simultaneous support for up to 8 toll-quality voice connections, 8 prioritized streaming media sessions and multiple Internet and network resource connections at Broadband speeds. And HomeRF accomplishes this with excellent comparative ratings for low cost, small size, low power consumption, interference immunity, security and support for high network density.

HomeRF has 10 Mb/s peak data rate in 2001 products with sufficient range for most residential applications. The data rate backs off to 5 Mb/s or lower if needed to extend the range well outside the typical home. HomeRF also supports very low-cost roaming for larger installations. HomeRF is the only technology with true toll-quality voice even in the presence of severe interference and the handset range is comparable to the best 2.4 GHz products on the market today. It is the only technology with support for all CLASS service features like call waiting, caller ID, forwarding to individual handsets, distinctive ringing, 911 breakthrough, etc. on an interoperable basis due to its DECT-based call stack. And unlike its 2.4 GHz band competitors, HomeRF's 2002 roadmap to 20 Mb/s or higher with full backwards compatibility is not dependent on further FCC rule changes.

Although this white paper highlights many desirable individual properties about both Bluetooth and IEEE802.11 for the Broadband Internet home, the conclusion that HomeRF is the premier choice ends up being quite obvious. Bluetooth simply lacks the capability to simultaneously support multi-line telephony, Broadband speed data access and multiple streaming sessions. IEEE802.11 variants fail completely to provide toll-quality voice services and compare poorly in critical aspects such as cost, size, power consumption and support for high network density. The serious shortcomings of IEEE802.11 for interference immunity and security are especially troublesome for mass consumer deployment.

IEEE802.11a deserves special mention. This technology has much in common with IEEE802.11b but it is legally scalable to much higher data rates (up to 54 Mb/s) at the expense of significantly reduced range at its peak data rate. By operating at 5 GHz, IEEE802.11a largely avoids much of the current interference concerns about IEEE802.11b and mitigates somewhat the network density limitations of IEEE802.11b. With aggressive cost predictions already being made for IEEE802.11a, it should quickly (by 2002) become the successor to IEEE802.11b for the enterprise networking application. However, IEEE802.11a will remain much more expensive than HomeRF or Bluetooth for many years to come and it currently fails completely to provide toll-quality voice services. It also suffers from the same security deficiencies as IEEE802.11b.

Even though Bluetooth and some IEEE802.11 variants will likely do well in their respective target applications outside the home, this is not in and of itself a compelling argument for service providers to compromise their revenue opportunities in the networked home. HomeRF is the clear choice for wireless networking of the Broadband Internet home and both service providers and their customers will benefit greatly by its widespread deployment. The world will adapt to the reality of multiple useful wireless connectivity interfaces for different applications, just as it already has adapted to a plethora of existing wired interfaces for the same reason.

Introduction

Home networking is essential for the Broadband Internet home

Broadband Internet deployment to the home in America is accelerating rapidly as supply chases insatiable demand. The content and services deployable to the home via the Broadband Internet may well drive one of the greatest social and economic shifts in human history – on par with indoor plumbing, electricity and the telephone. However, industry leaders have already clearly recognized that fulfillment of the true potential of the Broadband Internet in the home requires much more than connecting the "new fat pipe" to the "old home PC". For both service providers and consumers, the power of the Broadband Internet is unleashed only via a home network that can connect crucial "legacy" devices such as PCs, telephones and audio/video systems as well as new Internet-centric "appliances" many of which have not yet been conceived.

Consumers have really not planned ahead for home networking. Thus, the rollout of home networking will be largely "ad hoc" as service providers and/or consumers subscribe to or deploy individual applications. There are three basic home networking categories – dedicated wiring, re-use of existing home wiring and wireless. Within each category there are competing technologies and standards that complicate and confuse matters further. Many consumers will likely end up with networks composed from all three categories including multiple competing technologies because consumers usually do not like to compromise for any given application. Although generalizations are dangerous, industry experts often agree that dedicated wiring such as Ethernet or IEEE1394 offers the highest data rate performance (key to traditional video entertainment devices), existing wiring re-use such as HomePNA or HomePlug offers the lowest cost points (key to home automation and fixed location computing devices), and wireless such as HomeRF or IEEE802.11 offers the greatest mobility (key to personal information and communications devices). This white paper examines only the wireless technologies to show conclusively why HomeRF is best suited technically among the current contenders for wireless networking of the Broadband Internet home.

HomeRF Technology Overview

HomeRF was designed specifically for the Broadband Internet home

HomeRF, as the very name suggests, was developed from the beginning to bring wireless networking to the consumer using radio frequency (RF) devices. A typical HomeRF network for a Broadband Internet home consists of multiple device types as shown in Figure 1. HomeRF is unique among wireless networking standards in its ability to simultaneously provide Broadband speed Internet access and resource sharing, multiple streaming media sessions, and multiple toll-quality voice connections.

Figure 1: HomeRF Network Device Types

The technical explanation of how HomeRF works is of necessity extremely abbreviated here. The full HomeRF specification is about 500 pages long. The HomeRF specification, like most networking interface standards, describes fundamentally the lowest two layers of the seven-layer OSI network stack model as shown in Figure 2. The lowest layer, the physical (PHY) layer, sets most of the cost, data rate and range characteristics. The second layer, the data link control (DLC) or as used here the media access control (MAC) layer, defines the types of data services such as voice or prioritized streaming as well as other attributes like security, roaming and mapping to standard upper layers. In HomeRF the PHY and MAC layers are optimized together to provide superior interference immunity and high network density.

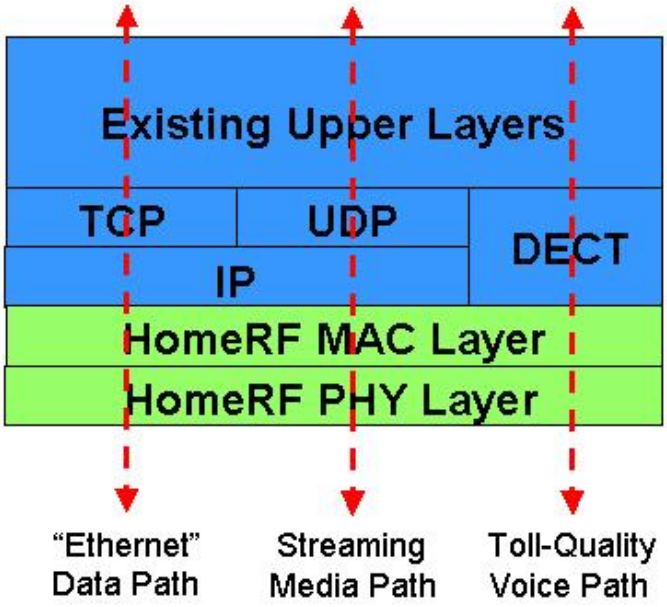

Figure 2: HomeRF Network Stack Model

The HomeRF PHY layer enables low cost, low power, and small size products

The HomeRF PHY layer of Figure 2 is common to all data service flow types shown in Figure 1. HomeRF products operate in the globally available 2.4 GHz band using frequency hopping spread spectrum at 50-100 hops/s. The radios are extremely simple - in fact they require only the same basic circuits as Bluetooth - such that very low cost, low power and highly integrated solutions are feasible today. First generation HomeRF products which as of this writing have captured 95%over 90% home wireless networking market share have peak data rates of 1.6 Mb/s and readily cover virtually all homes and small offices with 150 feet typical indoor range. Second generation HomeRF products due to ship mid-2001 use 10 Mb/s peak data rates while still providing whole home coverage. Both generations provide stellar low power consumption (< 10 mW standby with full TCP/IP connectivity) and small size (world's only Compact Flash WLAN). Third generation HomeRF devices are planned to be faster yet (~ 20 Mb/s) for shipments in the second half of 2002.

The HomeRF MAC layer combines toll-quality voice, streaming media, and data access

As indicated by Figure 2, the HomeRF MAC layer provides three distinct service flow categories:

- An asynchronous, connectionless packet data service (or "wireless Ethernet") typically used for TCP/IP traffic
- A prioritized and repetitive connection-oriented data service typically used for streaming media sessions using UDP/IP flows
- An isochronous, full-duplex, symmetric, two-way voice service typically used to map multiple toll-quality voice connections as defined by the DECT protocol

A very basic description of how the HomeRF MAC layer operates in the time domain is shown in Figure 3. Within each repeating frame, either 10 or 20 ms long depending on the presence of active voice calls, the bulk of the time (or bandwidth) is typically available for asynchronous data. However, within this asynchronous data period the first available opportunities to send packets are reserved sequentially for the prioritized streaming media sessions. Up to 8 sequentially prioritized simultaneous sessions are allowed but if fewer than 8 are present, the reservations are cancelled and the time (or bandwidth) is fully available for asynchronous data services.

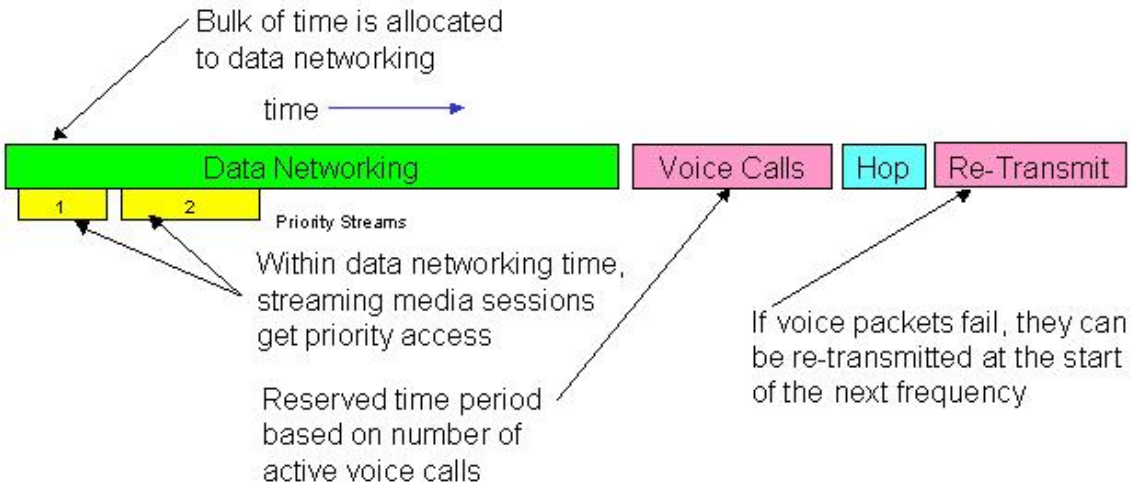

Figure 3: HomeRF MAC Layer Timing

Continuing with Figure 3, the last part of the repeating frame structure is divided into a series of fixed-length slots that are assigned as full-duplex pairs for two-way toll-quality voice communications based entirely upon the DECT upper-layer protocol. DECT, the Digital Enhanced Cordless Telecommunications system, is the world's most successful multi-line cordless telephony system in history with over 50M units in the field today and over 200M predicted by 2003. By designing the HomeRF MAC layer to map directly into DECT upper layers, HomeRF leverages not only thousands of thoroughly debugged protocol specification pages but also fifth generation custom DECT silicon and over 100 certified DECT handset suppliers that can easily convert to HomeRF. Note again that the time reserved for voice calls is directly proportional to the number of active connections and is adjusted dynamically as calls are added or dropped. Thus time (or bandwidth) available for data communications is always maximized. First generation HomeRF voice/data systems support 4 active handsets with a subjective voice quality score of 4.1 out of 5 (versus 4.3 for landline or 3.2 for digital cell phones). Second generation HomeRF voice/data systems will allow up to 8 active handsets at identical voice quality as landline.

The last "event" shown in Figure 3 is the voice connection re-transmits period. This is unique to HomeRF and provides excellent voice quality even in the presence of severe interference because the re-transmissions occur at a different frequency channel. The re-transmit feature is applied only to those rare voice packets that are actually lost in order to once again maximize the bandwidth available for asynchronous data traffic.

The Competing Wireless Networking Technologies for the Broadband Internet Home

In addition to HomeRF, two other wireless standards are often considered as candidates for home wireless networking – IEEE802.11 and Bluetooth.

IEEE802.11 – "Wireless Ethernet" for Enterprise Applications

IEEE802.11 is not actually a single interoperable standard but instead a family of at least 6 PHY layer specifications including work still in progress. A single common MAC layer is used in all cases and thus precludes the joint optimization of PHY and MAC together as HomeRF and Bluetooth have done. This standards effort began in 1989 and the clear focus from the beginning has been deployment in large enterprise networking environments – effectively a wireless equivalent to Ethernet. The most popular IEEE802.11 variant today is called IEEE802.11b and features a peak data rate of 11 Mb/s.

IEEE802.11b, like HomeRF and Bluetooth, also uses the 2.4 GHz band. But instead of simple conventional digital radio modulation and frequency hopping, IEEE802.11b uses a complex linear modulation and a coding variation of direct sequence spread spectrum. IEEE802.11b has already done very well by WLAN industry perspectives with IT managers for deployment in business offices within the enterprise. But despite this relative success, the proportion of enterprise workers using IEEE802.11b for corporate network access versus Ethernet is still extremely small. And the paradoxically-named IEEE802.11a ("b" preceded "a" in deployment) is now less than a year away from shipping with data rates up to 54 Mb/s in the much less interference plagued 5 GHz band. This will effectively obsolete IEEE802.11b in the enterprise market. Add in the reality that the home market will likely be much larger – consider the market size for cordless telephones at home versus the enterprise – and it becomes understandable that many IEEE802.11b advocates would like to position their products as ideal solutions for consumers in their homes. However, any reasonable and objective comparison shows that while IEEE802.11b is a decent technology for its intended purpose, it is technically inferior to HomeRF for the specific task of wirelessly networking the Broadband Internet home. And the very name of the technology does not have resonance with consumers like HomeRF.

Bluetooth – A Cable Replacement Technology for Ad Hoc Connectivity

The Bluetooth specification has much in common with the first generation PHY layer of HomeRF but the MAC layer is considerably different. This reflects the emphasis of the Bluetooth SIG (Special Interest Group) on solving very different connectivity problems than those undertaken by either HomeRF or IEEE802.11. The Bluetooth MAC layer is entirely time division multiple access (TDMA) based. Bluetooth can thus carry either voice or low rate data connections. With a peak data rate of only 1 Mb/s, the central focus of the Bluetooth SIG is achieving unconscious connectivity in a cable replacement paradigm. In fact, the Bluetooth SIG does not position its technology as a networking technology at all much less as the ideal solution for networking the Broadband Internet home. The main driving application for Bluetooth initially is connecting cell phones to hands-free accessories and information appliances.

However, the Bluetooth SIG is a very large organization (membership is free) and some members have been vocal about extending Bluetooth into home wireless networking applications. Thus the technical merits of Bluetooth for wireless networking of the Broadband Internet home will be explored here for completeness.

Detailed Comparison

The following attributes are considered here (in no fixed order of importance) as metrics for comparing the three contending home networking standards:

1. Cost
2. Toll-Quality Voice Support
3. Streaming Media Support
4. Data Throughput
5. Range
6. Power Consumption
7. Form Factor
8. Network Topology
9. Unwanted Interference Immunity
10. Self-Interference Immunity
11. Security
12. Roaming Outside the Home

For each attribute, the three contenders are rated here on an absolute basis (not relative to each other) specifically on their technical merits for the application of networking the Broadband Internet home. It is therefore possible for all three to receive identical ratings in any given attribute. The actual ratings used from highest to lowest are:

- Clear advantage for wireless networking of the Broadband Internet home
- Adequate for some or most aspects of wireless networking of the Broadband Internet home
- Distinct disadvantage for wireless networking of the Broadband Internet home

1. Cost

Lower Complexity gives HomeRF and Bluetooth a Cost Advantage over IEEE802.11

- HomeRF and Bluetooth have a clear advantage
- IEEE802.11 is at a distinct disadvantage

HomeRF and Bluetooth are simpler technologies than any of the popular IEEE802.11 variants. “Simpler” means fewer and/or less demanding RF semiconductor chips and passive components as well as less complex digital baseband chips. Generalizations are dangerous but for the next few years, it appears that for equivalent production volumes HomeRF and Bluetooth should have an advantage of about a factor of two in Bill of Materials (BOM) cost over any IEEE802.11 system.

Advocates of IEEE802.11 variants often dispute the magnitude of this cost difference as well as its implications for Broadband Internet networking deployment. They point out that the retail pricing of network interface cards (NICs) does not show the same magnitude difference as the BOM cost. For example, as of this writing the lowest price HomeRF NICs are about $80 each in retail versus about $130 each for IEEE802.11b – a factor of 1.6 instead of 2. However, this is mainly due to margin compression on the IEEE802.11b suppliers in the face of HomeRF (and pending IEEE802.11a) competitive pressure.

The other argument commonly put forth by advocates of IEEE802.11b for home use is that below $150 per NIC, price is of secondary importance. There is some truth to this for the early adopter and enterprise markets but this is completely false for mass deployment of the Broadband Internet. The key for pervasive presence of a networking technology standard with consumers, as clearly recognized by both HomeRF and Bluetooth, is that the technology must get built-in to pivotal devices – for the Broadband Internet home this means broadband gateways, Internet appliances and cordless telephones. For this to occur, cost is always of paramount importance and every cost “tier” – whether $50, $30, $20, $10, etc. – gets a given new technology built-in to ever increasing percentages of these pivotal devices. HomeRF and Bluetooth will always get to these important cost tiers ahead of IEEE802.11 variants and thus on this basis alone enjoy a significant advantage for becoming the de facto choice for wireless networking of the Broadband Internet home.

2. Toll-Quality Voice Support

Only HomeRF Supports Multi-Line Toll-Quality Voice with all Advanced Calling Features

- HomeRF has a clear advantage
- Bluetooth is probably adequate for some applications
- IEEE802.11 is at a distinct disadvantage

HomeRF is clearly the leader in this category for the reasons described in the Technology Overview section. Not only does HomeRF provide native support for 4-8 simultaneous high quality isochronous full-duplex voice connections, but it also leverages the highly successful DECT industry infrastructure, and makes specific accommodations for inevitable interference and other channel impairments.

Bluetooth was also designed from the beginning to accommodate voice traffic. It is conceivable to build a Bluetooth cordless handset and with the codec specified in Bluetooth the inherent voice quality is excellent. However, Bluetooth was really intended for an application like a wireless headset attachment for a cell phone. As such it lacks three essential features compared to HomeRF that detract from it as the choice for the Broadband Internet home. First, Bluetooth has no standardized interoperable call stack with CLASS features like HomeRF has with DECT. Second, Bluetooth voice connections have no MAC layer interference mitigation against complete packet losses as will likely occur from microwave ovens and other WLANs. This is not a problem for a wireless headset in a car but it is critical for whole-home cordless telephone operation. Bluetooth advocates have openly recognized this deficiency and have petitioned the FCC to change the 2.4 GHz rules such that future Bluetooth devices could have some measure of interference avoidance for this application. However, the FCC rules change process often takes many years to complete if the change is made at all. Finally, Bluetooth as a home network is limited to only two active calls (versus eight for HomeRF) and when two calls are present, the remaining data bandwidth is only similar to that of an analog modem (versus HomeRF where two active calls leaves data bandwidth that exceeds almost any DSL or cable modem connection).

IEEE802.11 completely fails to provide consumer grade voice support unless proprietary extensions are added (to date only for enterprise applications). Even with such extensions though, sending voice over IEEE802.11 is plagued by the presence of either unwanted interference or other IEEE802.11 networks – mechanisms to bound latency for voice in such scenarios are simply not present. And of course there is no interoperable call stack like DECT that IEEE802.11 has been designed to work with. Nor is there any existing industry infrastructure of cordless telephony technology that can be leveraged the way HomeRF can with DECT. Any service provider that believes multi-line, toll-quality voice is an essential ingredient of a wireless Broadband Internet home network should have serious misgivings about deploying any of the IEEE802.11 variants, especially interference prone IEEE802.11b, because of this voice support issue alone.

3. Streaming Media Support

Only HomeRF Supports Multiple Prioritized Streaming Media Sessions Independent of Voice and Data Traffic on the Network

- HomeRF has a clear advantage
- Bluetooth and IEEE802.11 are probably adequate for many applications

As described in the Technology Overview section, HomeRF provides native support for prioritized streaming media sessions within the asynchronous data framework of the protocol. Such prioritized streaming media sessions are not immune from all radio channel impairments, but they are not affected in any way by the amount of asynchronous data traffic on the network. Note though that by default two-way voice traffic in HomeRF does have higher priority than streaming media. HomeRF streaming supports a full range of options including multi-cast, two-way (i.e. videoconferencing) and receive-only destinations. Up to 8 simultaneous sessions are allowed with typical applications such as MP3 headsets, remote Dolby Surround Sound speakers and MPEG4 video distribution to Internet appliances.

Both Bluetooth and IEEE802.11 have the ability to support streaming applications as well. A Bluetooth wireless connection for an MP3 headset is very believable. But a multitude of voice, streaming and broadband data connections simultaneously over Bluetooth is not feasible due to its limited bandwidth and MAC architecture.

IEEE802.11b and IEEE802.11a both offer ample bandwidth for many streaming applications but unpredictable and unacceptable results occur if significant asynchronous data traffic appears on the network simultaneously. Various approaches are underway to tackle this problem. One is to simply change the MAC layer (as HomeRF and Bluetooth have) – this is the goal of the IEEE802.11e study group. However, this work will probably take a couple years and is constrained by the understandable desire for complete backwards compatibility. In the interim, some companies are taking their own proprietary approach but this leads to major interoperability problems and dilution of the IEEE802.11 "brand". This is not a serious problem for an individual consumer buying a solution for a given interesting application, but it is a serious concern for service providers deploying flexible infrastructure for the Broadband Internet home.

4. Data Throughput

HomeRF and IEEE802.11 have the necessary bandwidth but HomeRF's path to 20 Mb/s requires no regulatory changes – unlike the situation for IEEE802.11b

- HomeRF and IEEE802.11 have a clear advantage
- Bluetooth is at a distinct disadvantage

Although the definition of "broadband" can reasonably be as low as a couple hundred kb/s for deployment today, it is clear that the long term future for the Broadband Internet home will need networking technologies to support multi-Mb/s at a minimum. This eliminates the existing Bluetooth technology from further consideration. For example, in recent publicly reported testing, Bluetooth provided only about 200 kb/s peak throughput in a simple 2-node "network". Both HomeRF and IEEE802.11 can easily meet the Broadband data throughput requirements.

In the HomeRF case, second generation devices being deployed starting mid-2001 will have peak data rates of 10 Mb/s and the same low cost structure as today's first generation products. This corresponds to peak TCP/IP throughput of around 5 Mb/s (~ 25 times faster than Bluetooth). In the same timeframe IEEE802.11b devices of similar peak data rates and throughputs will also be approaching consumer price points. Thus for 2001 deployment it seems that both technologies are on par for this one consideration. However, the controversy on data rate for HomeRF versus IEEE802.11 comes in considering their future roadmaps to 20 Mb/s and beyond.

For HomeRF, the path to ~20 Mb/s operation is well understood and can be achieved with good in-home coverage, minimal extra cost and most importantly with no change to existing 2.4 GHz spectrum regulations anywhere in the world. Such products are targeted for the second half of 2002. However, for IEEE802.11 the options for 20 Mb/s and beyond are rather convoluted. First, there is yet another study group, IEEE802.11g, which aims to extend existing IEEE802.11b to ~ 20 Mb/s or higher peak data rates with full backwards compatibility. Unfortunately all the proposals under serious consideration by IEEE802.11g are illegal under existing FCC 2.4 GHz rules. It is virtually inconceivable that the rules can be changed before the end of 2002 to accommodate these proposed systems. Thus HomeRF will likely reach the 20 Mb/s mark ahead of IEEE802.11b in the USA. In the meantime, progress in building products based on the IEEE802.11a standard, which are in no way backwards compatible with IEEE802.11b products, has proceeded quickly. In fact by the end of 2001, enterprise-focused IEEE802.11a products operating at 24 and 36 Mb/s (eventually up to 54Mb/s) should start to become available.

5. Range

IEEE802.11 has Excellent Range Characteristics for Pristine, Interference-Free Environments while HomeRF has Good Full-Home Coverage even under Severe Interference

- IEEE802.11 and HomeRF have a clear advantage
- Bluetooth is at a distinct disadvantage

Another advantage for IEEE802.11 standards in addition to high data rates is the potentially good range performance relative to data rate under interference-free conditions. This is a direct consequence of the enterprise application focus of IEEE802.11 where range is critical because it sets the access point spacing and

thus drives the initial deployment cost. However, achieving good range in every product comes with a real price. More complex and expensive circuitry is required and power consumption and form factor are compromised. And in many residential applications, especially with voice and streaming media, interference-free range is less important than "range" under high interference and/or network density. Also, note that while IEEE802.11a has good range performance relative to 5 GHz technologies at comparable data rates, the IEEE802.11a range performance is significantly inferior to the 2.4 GHz technologies such as IEEE802.11b and HomeRF.

HomeRF has more that adequate interference-free range for almost all homes. For range-critical applications like cordless telephony, HomeRF is equal to or better than the best 2.4 GHz products on the market today. And the HomeRF range advantage is magnified in high network density or severe interference environments.

Bluetooth can also have more than adequate interference-free range for most residential applications when the "high power" devices are deployed. However, most analysts expect mainly "low power" Bluetooth devices with "room-sized" range to be deployed in cell phones and PDAs. Thus most consumers are likely to either associate Bluetooth with single room coverage instead of whole home coverage or be frustrated when mixing the two classes of devices. For this reason only, Bluetooth is seen to be at a disadvantage for this attribute.

6. Power Consumption

HomeRF and Bluetooth are Optimized for Extremely Low Standby Power

- HomeRF and Bluetooth have a clear advantage
- IEEE802.11 is at a distinct disadvantage

HomeRF and Bluetooth by nature of their modulation techniques and radio transceiver requirements have somewhat lower power consumption in active transmit or receive modes than any of the IEEE802.11 variants. However, in "standby" mode where a device is attached to a network but not actively transmitting or receiving, the differences between HomeRF and Bluetooth versus IEEE802.11 can be extreme (factor of 10-100). For enterprise applications such as networking desktop PCs or even laptops that often connect with AC power, power consumption has not yet been a major factor. But for small, light and personal information/communication appliances in the Broadband Internet home, low power consumption especially in standby mode is of paramount importance.

HomeRF achieves low standby power simply by exploiting the properties of a central controller and the extremely fast synchronization properties of its PHY layer. Bluetooth is solving a much more difficult problem than HomeRF in this respect. "Unconscious connectivity" in ad hoc networks means that extremely clever algorithms and very fast hopping are needed to minimize power consumption and keep connection latencies acceptable simultaneously.

7. Form Factor

Lower Complexity Enables HomeRF and Bluetooth to fit in Handheld Appliances

- HomeRF and Bluetooth have a clear advantage
- IEEE802.11 is at a distinct disadvantage

The most popular IEEE802.11 NIC form factor by far is the PC Card (or PCMCIA Card). This is more than adequate for the enterprise market where the laptop PC is the dominant mobile device. The smallest WLAN form factor in the world today is the Compact Flash Card – available only in HomeRF. It is reasonable to expect Compact Flash Bluetooth to follow shortly but the current level of integration for any IEEE802.11variant precludes this tiny form factor. Again the significance of this is not laptops in the enterprise but small, light and personal information/communication appliances in the home.

This discussion of form factor is somewhat analogous to cost. It is not that IEEE802.11 can never reach any given form factor, just that HomeRF and Bluetooth can always get there sooner. This provides yet another advantage for getting "built-in" to those pivotal devices in the Broadband Internet home.

8. Network Topology

Only HomeRF Supports Simultaneous Host/Client and Peer-Peer Operation

- HomeRF has a clear advantage
- Bluetooth and IEEE802.11 are probably adequate for most applications

HomeRF uniquely supports simultaneously both host/client and peer-peer communication – the best of both worlds. Host/client is ideal for toll-quality vice communications and Internet-centric applications such as webcasting. Peer-peer is ideal for efficiently sharing network resources like a DVD drive or a printer.

Bluetooth is inherently a point-multipoint system. It is effectively host/client except that in Bluetooth the host position is not fixed in advance. This does not make Bluetooth "broken" for home networking. But it is definitely not the most efficient use of bandwidth - which with Bluetooth is scarce to begin with.

The IEEE802.11 variants can operate in either host/client (via the Point Coordination Function or PCF) or peer-peer (via the Distributed Coordination Function or DCF). But not both modes simultaneously. To date all "home-focused" IEEE802.11b products operate only in DCF mode. To improve power consumption and/or introduce streaming media prioritization (to date on a proprietary basis), PCF is preferable though more complex and expensive to implement. Another study group, IEEE802.11e, is actively debating PCF versus DCF for proposed MAC changes in the standard such that streaming media can be better supported. One major barrier to simply adding peer-peer to PCF is the methodology by which IEEE802.11 handles roaming in the enterprise. Ironically, HomeRF – never noted for the enterprise application – has actually solved this problem completely in its second-generation specification that allows simultaneous host/client, peer-peer and roaming.

9. Unwanted Interference Immunity

HomeRF is Designed Specifically to Counteract Interference in the 2.4 GHz Band

- HomeRF has a clear advantage
- Bluetooth and IEEE802.11 are adequate for some applications

Of these three standards, HomeRF is the only one with a clear strategy to actively counteract the severe problems of in-band interference upon toll-quality voice communications as described in the Technology Overview section. Furthermore, HomeRF also provides a specific service for prioritized streaming media sessions to get caught back up with minimal latency in severe interference scenarios while not affecting the voice traffic. And HomeRF, like any frequency hopper, provides good overall immunity to interference for asynchronous data connections.

Bluetooth has some similarity to HomeRF in this regard but Bluetooth hops much faster – up to 1600 hops/s. Though this may have been motivated more by the needs of fast synchronization for unconscious connectivity in ad hoc networks, the net result is Bluetooth does not stay on an interfered channel for long. Unfortunately, the corollary is that Bluetooth returns to static interferers faster as well. So the net result is similar to HomeRF except in voice applications where Bluetooth's lack of a bounded latency MAC re-try mechanism can lead to poor voice quality near microwave ovens or other WLANs (such as IEEE802.11b).

The IEEE802.11b standard has been the subject of much controversy regarding the effects of unwanted interference – not all of which is fair and justified. For asynchronous data communications, most users will never notice a 10%-40% data throughput reduction that might occur for example from a microwave oven near an IEEE802.11b device. They would of course notice the factor of 30 reduction observed recently by a magazine writer when a Bluetooth device was active in the same laptop as an IEEE802.11b NIC, but this is a very extreme example. The big problem for IEEE802.11 networks is severe fluctuations in latency under interference which plagues streaming media applications and kills toll-quality voice calls. Note that IEEE802.11a is "immune" from interference problems today simply because the 5 GHz bands are virtually unoccupied. But in the long run it faces the same severe issues as IEEE802.11b does today – mitigated somewhat by the additional channels available at 5 GHz.

10. Self-Interference Immunity

HomeRF and Bluetooth are More Scalable than IEEE802.11 for High Density Residential Applications

- HomeRF and Bluetooth have a clear advantage
- IEEE802.11 is at a distinct disadvantage

Both HomeRF and Bluetooth enjoy the advantages here of having many more independent channels than for example IEEE802.11b which has only 3. But the difference in performance goes beyond number of physical channels to the very philosophy these standards chose based on their target applications.

The IEEE802.11 committee focused on the need of a large enterprise deployment – just as IEEE802.3 (Ethernet) had before them. Here the goal was to maximize the overall system throughput – not an individual user or even an individual "cell" of users. Thus all IEEE802.11 compliant devices defer to or shut down in the presence of any other active IEEE802.11 device detectable anywhere on their physical channel. Even if the device belongs to another private network in another building at such a distant range that it can not possibly demodulate the actual data and the level of interference is so low that it would not impede local connectivity.

While this approach makes perfect sense to enterprise IT managers, consumers see things very differently. They do not accept that it is "OK" to sacrifice their specific application such as a streaming session or a toll-quality voice call to the greater good of maximizing overall wireless network throughput in their neighborhood. Consider the following graphic example. House A has an Internet appliance several feet away from a residential gateway that is streaming MPEG4 video to it. Elsewhere in the neighborhood, House B has exactly the same scenario going with a different video in play. Because Broadband Internet is so popular in this neighborhood and this service provider chose to deploy IEEE802.11b, both independent networks for Houses A and B are on the same physical channel. Unfortunately for these customers one or both of these video streaming sessions will be stopped to wait for the other even though both have signals easily strong enough to overcome the effects of the distant "interference". So these consumers suffer and this service provider will not maximize its revenue. In both HomeRF and Bluetooth, this scenario would have a much different outcome. If the signal strength is strong as it is in this example, both sets of transmissions would go through successfully even in the much more unlikely case of coincident physical channel. HomeRF and Bluetooth were designed such that distant similar networks with independent network IDs are ignored for the obvious reasons relevant to home networking or ad hoc connectivity.

Thus self-interference greatly limits scaling IEEE802.11 networks to urban environments where independent network density is high. This problem is especially acute if latency-sensitive applications like toll-quality voice or streaming media are involved. IEEE802.11a is better than IEEE802.11b in this regard because there are more physical channels but the inherent limitation of deferring to distant unrelated networks remains.

11. Security

Although any network has its vulnerabilities, HomeRF is inherently more secure than Bluetooth or IEEE802.11

- HomeRF has a clear advantage
- Bluetooth is probably adequate for some applications
- IEEE802.11 is at a distinct disadvantage

Security is a real concern for consumers with regards to wireless communications. Analog cordless phones, analog cell phones and CB radios have trained them to see wireless as easy to eavesdrop. With even basic digital encryption and authentication, denying the casual eavesdropper is easy and all three standards here accomplish this adequately.

While none of these systems can truly defend against attack by a professional eavesdropper (like the CIA) with unlimited resources due to the lack of PHY layer security, there are still clear and important distinctions between the different technologies. For example, in IEEE02.11b every symbol transmitted contains the single cover code (1,1,1, -1,1,1, -1,1) and compliant devices operate continuously in "promiscuous" mode where packets from any network ID are considered. Thus as researchers at Berkeley have shown recently, any compliant device can demodulate MAC layer bits to allow the attacker to work off-line and break the password. Furthermore, a

compliant device can easily be put into a mode where it joins a network without permission and either searches for network traffic and resources or sends packets to aid in breaking the relatively weak “WEP” encryption. In fact a compliant IEEE802.11device can also be used to insert unauthorized encrypted packets into the wireless network or even the backbone wired network, all without knowledge of the encryption key.

In contrast, HomeRF was designed from the beginning to provide much better security for consumers who, unlike IT managers in the enterprise, are not likely to run upper layer security measures over their wireless network. The defects highlighted for IEEE802.11 simply are not present in HomeRF. For example, consider that a compliant IEEE802.11 device can present another network’s unique ID to the eavesdropping host device in seconds without prior knowledge. With HomeRF, the host would have to “guess and search” – a process that would typically take at least 1 year to find a single valid unique network ID. Furthermore, HomeRF devices have specific measures that make it impossible to send unauthorized encrypted packets into the network even if someone did use a non-compliant device to learn the network ID. And the HomeRF standard uses 128 bit encryption rather than the 40 bits in IEEE802.11 so decoding the key is extraordinarily more difficult.

Finally, all three systems have some vulnerability to hostile denial of service attacks but for IEEE802.11 the ease is almost comical if not tragic. For HomeRF and Bluetooth, effectively shutting down any given target network is feasible only if the attacker builds custom hardware and uses large interfering energies (which is illegal). But shutting down many networks (i.e. an entire neighborhood or a large building) is extraordinarily difficult because of the many physical channels and the way HomeRF and Bluetooth ignore commands from foreign networks. However in direct contrast, IEEE802.11b or IEEE802.11a compliant networks are very susceptible to mass denial of service attacks that can be made remotely (and legally) with little interfering energy or interfering duty cycle.

12. Roaming Outside the Home

The good thing about mobile devices is that they can move around

- HomeRF, Bluetooth and IEEE802.11 are all adequate

Most of the interesting devices within the Broadband Internet home will logically stay within the home and its immediate vicinity. Few will likely roam far but for those devices that do such as a laptop computer or a PDA, being able to use the same wireless NIC is certainly desirable. All three standards considered here have stories for roaming outside the home. None is perfect. But this will probably matter very little in the end. There are few precedents for usage outside the home being a prerequisite for success of a consumer technology within the home. If anything the past 20 years have shown exactly the opposite – new technologies usually start with consumers and then migrate, often in modified form, to business environments.

Of the three standards, Bluetooth has both the best vision for roaming outside the home and the least current reality. The whole premise of Bluetooth is “unconscious connectivity anywhere, anytime”. And indeed if Bluetooth does get built-in to every cell phone, a true platform for roaming outside the home, the vision can become a powerful reality.

Of the three standards, IEEE802.11 has the most over-hyped story on this topic by far. In fact IEEE802.11b advocates trying to enter the home networking market have made this issue their central theme. They argue that all corporate employees will have as manifest destiny an IEEE802.11b NIC in their laptop PCs so that when they take their laptops home one node in the home network is already paid for. Nice argument – but it falls apart upon closer scrutiny. First, the actual penetration of IEEE802.11b into corporate enterprises or educational campuses is non-existent compared to Ethernet (which by this argument should be the runaway lead candidate for all home networking). And second, only a fraction of corporate laptops actually go home on a regular basis. It is simply inconceivable that service providers would base their long-term wireless home networking strategy on this tiny user segment and their narrow application. Furthermore, IEEE802.11b is on the verge of being obsolete for mainstream enterprise deployment due to the more robust and much faster IEEE802.11a products shipping by the end of 2001.

Finally of the three standards, HomeRF has the least understood story on this topic. In reality many first-generation HomeRF products (which currently hold 95% market share for home wireless networking) can roam outside the home today on to the more than 50,000 OpenAir networks in enterprises, educational and healthcare campuses, hotels and airports. In fact the largest WLAN public access provider today provides both IEEE802.11b and HomeRF/OpenAir access at all locations. The second-generation HomeRF specification explicitly adds

support for low-cost roaming of HomeRF devices independent of OpenAir. Finally, by 2002 combination HomeRF/Bluetooth devices are expected to be commonly available which gives the rich capabilities of HomeRF within the Broadband Internet home and the projected pervasiveness of Bluetooth for operation outside the home.

Summary – HomeRF is the Clear Choice for the Broadband Internet Home

Collecting the technical ratings for all three standards across this exhaustive list of attributes relevant to the needs of the Broadband Internet home produces the results summarized here as Table 1:

Attribute	HomeRF	Bluetooth	IEEE802.11
Cost	✓	✓	X
Toll-Quality Voice Support	✓	~	X
Streaming Media Support	✓	~	~
Data Throughput	✓	X	✓
Range	✓	X	✓
Power Consumption	✓	✓	X
Form Factor	✓	✓	X
Network Topology	✓	~	~
Unwanted Interference Immunity	✓	~	~
Self-Interference Immunity	✓	✓	X
Security	✓	~	X
Roaming Outside the Home	~	~	~
✓ -- Indicates a clear advantage for wireless networking the Broadband Internet home			
~ -- Indicates adequate for wireless networking the Broadband Internet home			
X -- Indicates a distinct disadvantage for wireless networking the Broadband Internet home			

Table 1: Summary comparison of results.

From Table 1, HomeRF clearly emerges as the premier technical choice for wireless networking of the Broadband Internet home. Bluetooth has many good features but it falls short on bandwidth to support simultaneous multi-line telephony, Broadband speed data access and multiple streaming sessions. Bluetooth also has many products that will have inadequate range for whole home usage. The IEEE802.11 standards generally have good bandwidth and range (if interference is ignored) but fail completely to provide toll-quality voice services. Furthermore, the IEEE802.11 variants compare poorly to HomeRF or Bluetooth in critical areas such as cost, size, power consumption, interference immunity, security and ability to scale to high network density.

Overall Positioning of the Competitive Standards

HomeRF for the Home, IEEE802.11 for the Enterprise, Bluetooth for Mobile Cable Replacement

At this point a reader could reasonably wonder that if HomeRF is so excellent for the Broadband Internet home, why do Bluetooth and IEEE802.11 even exist at all? And why do respected industry leading companies known for their technical expertise back them each with such determination? The reason is that both Bluetooth and IEEE802.11 have strong technical and organizational strengths to succeed in markets complementary to HomeRF. This is illustrated graphically in Figure 4.

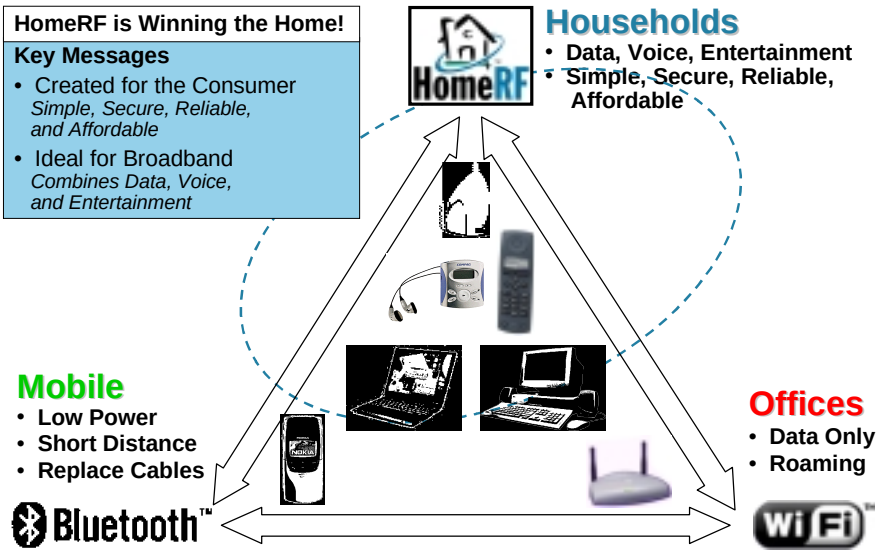

Figure 4: Positioning HomeRF, Bluetooth and IEEE802.11

Many people in the electronics industry with limited background in wireless find the "answer" provided by Figure 4 to be extremely unsatisfying and frustrating. Some even predict a "consumer revolt" against the ridiculous situation of three non-interoperable wireless data standards all using 2.4 GHz to do what at first glance appears to be the "same thing". But this characterization is really unfair.

Radio is by nature a very unbounded media with many degrees of freedom, cruel governing physics, and even crueler governing spectrum regulations. And radio has always been sold to consumers for individual specific applications not broad general-purpose infrastructure. The "wired-interface" industry certainly has no better track record by this measure. Why do consumers accept PCs with a mouse port, a keyboard port, a game port, a video port, a parallel port, an RS-232 port, a SCSI port, a docking adapter, a modem jack, an Ethernet jack, an IEEE1394 port and a USB port? Why don't consumers demand that the "wired-interface" industry get its act together and provide us one port for all wired interfaces?

The truth is consumers not only accept a plethora of optimized wired interfaces, they demand it. And wireless will be the same way. Thus, service providers should deploy wireless networking infrastructure for their application – the Broadband Internet home – based solely on delighting their target customers and maximizing their revenue. The clear choice is HomeRF and what happens in other segments of the wireless connectivity market is of secondary importance at best.