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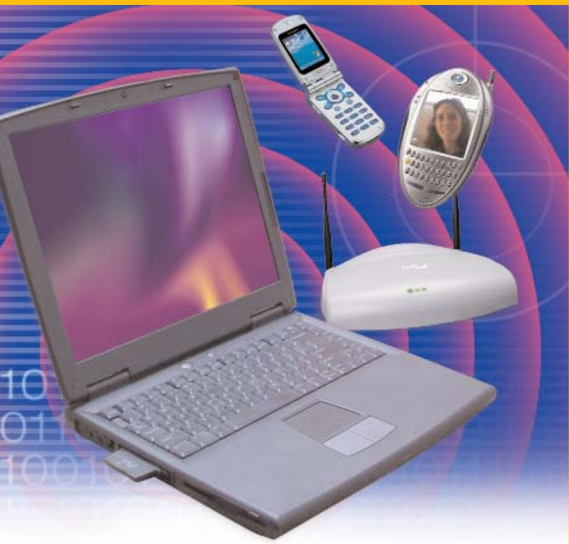

Intel® Technology Journal

Wireless Technologies

On the Union of WPAN and WLAN in Mobile Computers and Hand-Held Devices

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On the Union of WPAN and WLAN in Mobile Computers and Hand-Held Devices

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ABSTRACT

With the introduction of Intel® Centrino™ mobile technology and Personal Internet Client Architecture (PCA), today's mobile notebooks and mobile devices are advanced communication platforms with multiple wired and wireless technologies. Of those wireless technologies, Wireless Personal Area Networks (WPANs) are a key ingredient for current and future versions of Intel Centrino mobile technology and PCA. This paper focuses on how WPAN technology such as Ultra Wideband (UWB) or Bluetooth* technology enables new usage models when used in conjunction with Wireless Local Area Networks (WLANs) technology. Several key usage models of WPAN and WLAN interaction are explored in detail. In addition to the proposed simultaneous use of WPANs and WLANs, we elaborate on integration and wireless coexistence issues for WPANs and WLANs. Both radios operate in the 2.4 GHz Industrial Scientific Medical (ISM) band and therefore interfere with each other. We explain how Intel's coexistence solution diminishes the potential interference issues that result from this simultaneous use of multiple wireless technologies.

We explore how the new usage models are enabled by the union of WLAN and WPAN. We scan the WLAN and WPAN environment and highlight some of the major new advances. For WPAN, we review features in the upcoming 1.2 version of the Bluetooth specification as well as the formation of the IEEE 802.15.3a Working Group (WG). For WLAN, we explore the rapid advances in security and Quality of Service (QoS) definitions of IEEE 802.11 WGs, and the new IP protocols that support mobility as defined by the Internet Engineering Task Force (IETF). These new usage models drive improved wireless capabilities for mobile platforms and introduce new scenarios that the mobile user can take advantage of with Intel's next-generation notebooks and hand-held devices.

INTRODUCTION

Intel Centrino mobile technology and Personal Internet Client Architecture (PCA) are key ingredients for enabling the union of Wireless Local Area Networks (WLANs) and Wireless Personal Area Networks (WPANs) and the new usage models enabled by this union. In the first part of this paper we briefly review the technology behind Intel Centrino mobile technology and PCA and we give a short primer on the main wireless technologies that are discussed in the paper. In the second section, we examine how the wireless networking capabilities of Intel Centrino mobile technology and PCA enable new usage models. We then explore the various technology drivers that are influencing these new usage models. In the final section we address platform integration issues and coexistence solutions.

Intel Centrino Mobile Technology Overview

Intel Centrino mobile technology combines the Intel® Pentium® M processor, the Intel® 855 chipset family, and the Intel® PRO/Wireless 2100 Network Connection, as shown in Figure 1.

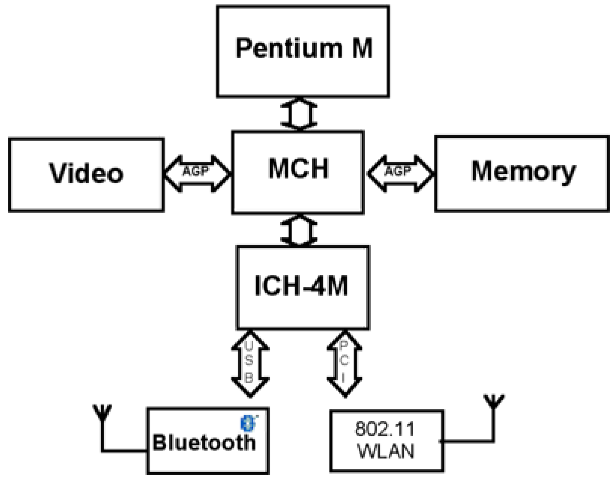

Figure 1: Intel® Centrino™ mobile technology

The Intel Pentium M processor micro-architecture is optimized for high performance and low power. The Intel 855 chipset family consists of two components: the Intel® 855PM Memory controller Hub (MCH) and the Intel® 82801DBM I/O Controller Hub (ICH-4M). The Intel PRO/Wireless 2100 Network Connection is the integrated Wireless LAN (WLAN). All components were designed, optimized, validated, and tested to work together with mobility in mind. Many Intel Centrino mobile technology laptops are adding WPAN capabilities. With the addition of WPAN, new usage models are enabled and integration issues need to be considered. These new usage models and integration issues are addressed in this paper.

The Intel Personal Internet Client Architecture

The Intel PCA [15], [16] partitions the device configuration of the traditional cellular platform into an Applications Subsystem (APPS), a Communication Subsystem (COMM), and a Memory Subsystem. This partitioning allows application development to evolve independent from communication standards. The Intel PCA provides open programming interfaces and services between physical platforms (including communication) and application software, thereby facilitating faster development of the application and abstracting the underlying physical resources.

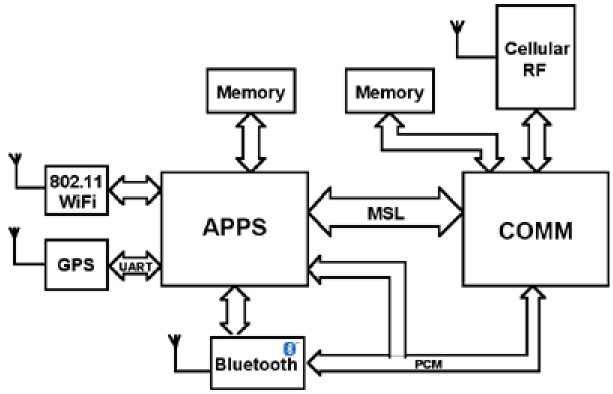

Figure 2: PCA with wireless subsystems

The COMM is based on the Intel® Micro Signal Architecture digital signal processor (DSP), and it provides the APPS the services to access cellular wireless networks that are independent of the physical medium. The COMM services are independent of the air-link technology, and they are responsible for maintenance of the connection to an appropriate wireless network for telephony and data services in support of the APPS.

The APPS is based on Intel® XScale™ technology and is capable of running an operating system, user interface, and applications. It manages resources such as user input/output devices, expansion devices, memory interfaces, power management, and communication interaction with the COMM. In addition, the APPS processor hosts the wireless subsystems including the Bluetooth, 802.11, and the Global Positioning System (GPS), which provide various kinds of data connectivity. All of these wireless technologies are described in the next section.

Figure 2 describes a block diagram of an implementation example of a cellular mobile system in PCA architecture. The COMM has an RF connection to the cellular system and is connected to the APPS using a standard link called the Intel® Mobile Scalable Link (MSL). The MSL hardware is capable of running up to 52 MHz or has a data throughput of 208Mbps, and it is used mainly for exchanging data packets between subsystems. The Bluetooth baseband+radio chip is connected using a Universal Asynchronous Receiver Transmitter (UART) connection; it also has serial Pulse Coded Modulation (PCM) interfaces to both APPS and COMM processors. The PCM connection to the APPS is used during audio scenarios handled by the APPS processor such as voice memo pad (VMP), voice recognition (VR),

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calendar/incoming e-mail alerts, and so on. The direct connection to the COMM processor is used during cellular voice calls. Finally, the 802.11 MAC and PHY are connected using some proprietary interface.

WIRELESS TECHNOLOGIES PRIMER

The increasing demand for a variety of high-rate data services along with the requirement for reliable connectivity anywhere at anytime demands that several different wireless subsystems be integrated into a single hand-held device or into a mobile notebook computer.

The market share of devices enabled with Bluetooth wireless technology has been growing constantly. Analysts predict that by 2005 the number of mobile handsets enabled with Bluetooth wireless technology will be as high as 800 million units with a market penetration of 65% [9]. Side by side with the Bluetooth technology, the 802.11 WLAN is also becoming the *de facto* wireless standard for high-rate Local Area Networks (LANs), with more and more wireless networks being deployed around the world every day. In addition, as more and more location-based data-services and emergency services (E-911) are becoming commercially available, the demand for GPS receiver integration in hand-held cellular devices increases accordingly.

Following, we briefly describe the main wireless technologies mentioned above, which are being considered for both PCA and Intel Centrino technology. Our intention is not to cover all the issues of a specific technology, but only highlight the main features describing how that specific technology can serve as a data gateway.

- ***Wireless cellular technologies**:* The wireless cellular systems being considered in this paper belong to the second generation (2G), 2.5G, and 3G. The majority of the cellular networks being deployed around the world is based on the Global System Mobile (GSM) standard. This is a TDMA standard that can operate in several radio frequency (RF) bands. The most usable of these bands are the 900MHz band, the 1800MHz band (a.k.a. digital communications system (DCS) band), and the 1900MHz band (a.k.a. personal communications system (PCS) band). Each of these operation bands is divided into channels in widths of 200kHz. The 200kHz channel is divided into eight time slots and is shared in a time division manner between eight different users. The GSM network is used mainly for conventional telephony services, but can also accommodate internet browsing via circuit switched dial-up networking (DUN), providing raw data rates of 9.6kbps.

The evolution for the 2.5G of the TDMA standards includes the General Packet Radio Service (GPRS) and the Enhanced Data Rates for GSM Evolution (EDGE). The GPRS standard provides a packet network on dedicated GSM channels. The GPRS retains the original modulation formats specified in the original 2G GSM standard, but uses a completely redefined air interface in order to better handle packet data access. GPRS subscriber units are automatically instructed to tune to dedicated GPRS radio channels and particular time slots for "always on" access to the network. The GPRS standard allows a single subscriber unit to occupy multiple consecutive time slots in order to increase its data throughput. When all eight time slots of a GSM radio channel are dedicated to GPRS, an individual user is able to achieve as much as 171.2kbps [20].

EDGE (which is sometimes referred to as Enhanced GPRS, or EGPRS) includes a new digital modulation format in addition to the standard GSM modulation. EDGE allows nine different air-interface formats known as multiple modulation and coding schemes (MSC), with varying degrees of error control protection, to be selected according to the instantaneous network and operating conditions. Similar to GPRS, the EGPRS standard also allows a single subscriber unit to occupy multiple time slots for increasing its data capacity. In practical network conditions, when all eight GSM time slots are being dedicated to a single user, the EDGE is capable of providing a raw peak throughput data rate of 384kbps.

Third-generation (3G) systems promise unparalleled wireless access such as Voice over Internet Protocol (VoIP) and unparalleled network capacity. The eventual third evolution for the 2G GSM networks is based on wideband code division multiple access (W-CDMA), also known as Universal Mobile Telecommunications Service (UMTS). W-CDMA assures backward compatibility with the 2G GSM networks, as well as with the 2.5G TDMA networks such as EDGE. The W-CDMA air interface was designed for "always-on" packet-based wireless services and can support packet data rates of up to 2.048Mbps.

Mobile handsets based on Intel PCA technology will support all 2G, 2.5G, and 3G cellular technologies mentioned above, and will provide constant internet connectivity with a high quality of service (QoS) throughout the entire coverage area of the cellular network, including regions that are not covered by other internet access means such as 802.11, described next.

- ***IEEE 802.11*** (a.k.a. Wi-Fi, or Wireless Local Area Network (WLAN)): This was defined by the IEEE in 1997 as a standard that would replace the wired Ethernet connection cables with a wireless connection. The 802.11 standard is limited in scope to the Physical (PHY) layer and the Medium Access Control (MAC) sub-layer, with MAC origins to the IEEE 802.3 Ethernet standard. The 802.11 standard definition for the Physical layers standard includes definitions for Physical Layer Convergence Procedure (PLCP) and Physical Medium Dependent (PMD) sub-layers. The 802.11 has three major extensions that are being considered today. The first extension is called 802.11a. It operates in the 5GHz band with twelve separate non-overlapping channels. As a result, you can have up to twelve access points (APs) set to different channels in the same area without them interfering with each other. The 802.11a uses orthogonal frequency division multiplexing (OFDM) PHY, which divides a data signal across 48 separate sub-carriers within a 20MHz channel to provide transmission rates of 6, 9, 12, 18, 24, 36, 48, or 54Mbps.

  The second extension is called 802.11b and is the basis of the majority of wireless LANs in existence today. The 802.11b operates in the 2.4GHz ISM band and uses direct sequence spread spectrum (DSSS) PHY with complementary code keying (CCK) modulation to disperse the data frame signal over a relatively wide (approximately 30MHz) portion of the 2.4GHz frequency band. The data rates supported by the 802.11b are 1, 2, 5.5, and 11Mbps.

  The third extension, which has recently been approved, is called 802.11g. 802.11g broadens the 802.11b's data rates to 54 Mbps within the 2.4 GHz band using OFDM, similar to the one being used by the 802.11a. Similar to 802.11b, 802.11g operates in the 2.4GHz band, and the transmitted signal uses approximately 30MHz, which is one third of the band. This limits the number of non-overlapping 802.11g APs to three, which is the same as 802.11b.

- ***GPS:*** A growing number of hand-held devices integrate Global Positioning System (GPS) receivers in their design. GPS is used for both security applications such as E-911 and location-based services. Similar to the 802.11b, the GPS also uses the DSSS RF technology that operates in the spectrum band of 1570-1580MHz. The GPS receiver measures the time of arrival (TOA) for signals transmitted from 24 satellites, which are in orbit around earth. The TOA data from three or more satellites is used for calculating the instantaneous location of the GPS receiver. The acquisition of the satellite signals usually requires a line of sight (LOS) between the antenna and the transmitting satellite thereby making GPS less applicable for indoor locations. The signal acquisition is sometimes quite lengthy and when it is, it reduces the idle periods of the system incorporating a GPS receiver. In order to shorten it and increase the robustness of the system for indoor operations, it is often used to integrate a variant of the GPS called "assisted GPS." With assisted GPS, the mobile phone receives initial information about the satellites above it and uses this information to reduce the acquisition time and improve its GPS reception sensitivity.

- ***Bluetooth Technology:*** The Bluetooth specification defines a frequency-hopping spread spectrum (FHSS) wireless system, operating in the 2.4GHz band. It was designed as a wireless cable replacement and as a Personal Area Networking (PAN) technology. The current revision of the Bluetooth specification (1.1) supports data rates as high as 723kbps and can accommodate (unlike 802.11 technology) both asynchronous (i.e., packet switched) data and synchronous (i.e., circuit switched) audio transmissions. More information on Bluetooth technology is found in the coming sections.

INTEL CENTRINO MOBILE TECHNOLOGY AND PCA USAGE MODELS

With Intel Centrino mobile technology and the Intel Personal Internet Client Architecture (PCA), today's mobile notebooks and mobile devices are advanced communication platforms and can interact with one another to enable common usage models. Additionally, these communication advancements are due to the integration of Wireless Local Area Network (WLAN)- and Wireless Personal Area Network (WPAN)-enabled mobile notebooks with Intel Centrino mobile technology and are also due to mobile phones/PDAs that use PCA so that new usage models are relevant to each platform.

Common Usage Models

One of these key common usage models is the interaction of the mobile notebook with the mobile phone. In this model, the mobile phone provides access from its Wireless Wide Area Network (WWAN) to the mobile notebook. The mobile notebook and mobile phone use their WPAN radio to wirelessly exchange data. The mobile phone acts as an access point (AP) (or a modem) to the mobile notebook to share its General Packet Radio Service (GPRS), Enhanced GPRS (EGPRS), or 3G data connection with other mobile devices to access the Internet.

Another key usage model of mobile notebooks and mobile phones is the use of the mobile notebook as a data store. In this model the mobile phone is used to access information stored on the laptop. For example, calendar, contacts, and mail information stored on the mobile notebook can be accessed and/or can synchronize the mobile phone via the WPAN interface. Additional information such as maps, media files, and pictures can be accessed by using the same mechanisms.

Intel Centrino Mobile Technology Usage Models

With these communication advancements in Intel Centrino mobile technology, several new usage models are more pertinent for the mobile notebook. One example is the use of the mobile notebook as a "mobile router." A mobile router is a device with multiple networking interfaces that routes network packets via multiple network interfaces just as a normal router would, but the difference is that the mobile router moves from network to network. Notebooks with Centrino Mobile Technology with WLAN and WPAN capability are ideal mobile routers. The mobile notebook uses the WPAN interface to connect a user's personal devices (phone, PDA pagers, watches, etc.) to the Internet via other networking interfaces. The mobile notebook uses its WLAN connection to connect to a wireless hotspot to provide internet access to the user's personal devices. As the mobile notebook moves from hotspot to hotspot, internet connectivity is maintained for the user. Personal devices, which are connected by a WPAN connection, are not directly affected by the movement because they maintain the same WPAN connection with the mobile router and move with the mobile router. The mobile router performs the necessary tasks to maintain connectivity as the mobile router moves from hotspot to hotspot.

Another key usage model is the use of Voice over IP (VoIP) with Centrino mobile technology. The integration of Intel Centrino mobile technology with VoIP will allow the mobile notebook user to make and receive voice calls. The WLAN interface is used to provide connectivity to the Internet to send and receive the VoIP packet. The WPAN interface is mainly used for cable-replacement applications such as connecting to an audio headset while the phone acts as an audio headset to send and receive the audio for the VoIP session.

PCA: Key Wireless Usage Models

Data is the name of the game today and in the future. Any design that will be able to provide high-rate, versatile, and reliable connectivity will be the design of choice. The essence of the PCA is to allow data streaming by various means, simultaneously and without mutual interference between the involved subsystems. Data from the outside world can stream into the system through either the cellular link (i.e., Global System Mobile (GSM), GPRS, EGPRS, and the Universal Mobile Telecommunications Service (UMTS); through 802.11, Bluetooth link (e.g., PAN, downloaded JAVA applications enabled with Bluetooth technology, etc.), Infra Red Data Association (IrDA), serial-cable connections (e.g., the Universal Asynchronous Receiver Transmitter (UART), the Universal Serial Bus (USB), Secure Digital (SD) cards, etc.), and a Global Positioning System (GPS). Any data, whether they are downloaded through the cellular link, or via any peripheral subsystems connected directly to the Applications Subsystem (APPS) processor will be processed by the APPS processor. The reason for the partitioning is twofold. First, it ensures that downloaded applications (e.g., JAVA games) can be executed without overloading the Communication Subsystem (COMM) processor. Second, it disables any ability of the application to harm the execution of the COMM processor, (e.g., by Trojan horse virus attacks, by memory leakages as a result of poor application design, etc.). Overall, this partitioning enables continuous connectivity to the cellular network to be maintained.

The variety of connectivity means, together with the requirement for simultaneous coexistence of those means, enables the support of hybrid usage models combining data and voice. In the following section, we review some usage scenarios and briefly describe how the wireless subsystems are being used in each of them. Speaker independent voice recognition (SIVR) can be used for hands-free dialing, smart phonebook browsing, and so forth. Natural accessories for this kind of application are hands-free devices, enabled with Bluetooth technology, such as headsets and wireless car kits, for which the PCA device serves as an audio gateway (AG). As an example, a scenario that combines voice with data is video conferencing. In this scenario, video data from the remote site can stream into the system either through the cellular network or via an 802.11 hotspot, located in local coffee shops, at the office, or at an airport. The video data can be either processed by the APPS processor for display on the PDA screen. Alternatively, it can be routed into the Bluetooth protocol stack for streaming into a projector enabled with Bluetooth technology, thereby enabling it to be displayed on a bigger screen. The video and audio of the near end can stream from a digital camcorder, enabled with Bluetooth technology, into the APPS processor and from there either over cellular or WLAN to the other side. The audio can be processed by the APPS and sent over the Bluetooth link right into the user's Bluetooth headset. Another usage example of Bluetooth technology that is becoming more and more popular involves location-based information. A user's location can be measured either by GPS, WLAN hotspots, or even by roadside Bluetooth kiosks, and information can be provided on such things as traffic jams, retail sales in malls on the user's route, etc. Clearly, this information would have to be retrieved while the user is on a voice call using his or her Bluetooth headset or car-kit, so some coexistence mechanism that enables the cellular, the Bluetooth technology, the WLAN, and the GPS is required. Such a mechanism is described later in this paper.

TECHNOLOGY-ENABLING DRIVERS

During the past couple of years several key technologies have been developed or are in the process of being developed that help to enable the new usage models described in previous sections. These key technologies are major driving factors in enabling the union of Wireless Local Area Networks (WLANs) and Wireless Personal Area Networks (WPANs). Of these new technologies, we review four in this paper: the IEEE 802.11i standard, the 1.2 version of the Bluetooth SIG specification, Ultra Wideband (UWB) (IEEE 802.15.a) technology, and the Internet Engineering Task Force (IEFT) mobility drafts. Each of these key technologies is a major driver in an effective union of WLANs and WPANs.

IEEE 802.11i

The IEEE 802.11 security task group (Tgi) is developing specification improvements to increase the security of the current 802.11. There has been a high market demand for an interoperable WLAN security solution, and Wi-Fi Protected Access (WPA) is the wireless industry's response. WPA is a subset of the work from the IEEE 802.11 security task group and addresses the vulnerabilities that the Wired Equivalent Privacy (WEP) defined in the 1999 standard; it does not require a hardware upgrade to support it. WPA is a transitory step between the original WEP security solution and the forthcoming IEEE 802.11i standard. WPA provides additional security mechanisms to ensure that enterprise and consumer wireless users' data are protected. This is the first crucial step in enabling the new usage models described in the previous usage models.

The Bluetooth 1.2 Specification and New Profiles

The 1.2 version of the Bluetooth SIG specification, scheduled to be formally adopted by the end of Q3 '03, includes some new features as well as enhancements of existing features from the 1.1 specification. The improvements over the 1.2 specification are faster connection establishment, adaptive frequency hopping (AFH), extended Synchronous Connection Oriented (SCO) links (eSCO), scatter mode (for enhancing the PAN working mode), anonymity mode (for improved user's privacy, in coordination with the emerging location technologies enabled with Bluetooth technology), and some improvements in the Logical Link Control and Adaptation Protocol (L2CAP) Quality of Service (QoS) mechanisms. A brief description of the relevant portions is given below.

Adaptive Frequency Hopping

The high density of radio frequency (RF) systems in the Industrial, Scientific, Medical (ISM) band at 2.4GHz, including microwave ovens, cordless telephones, wireless systems such as the 802.11 b & g, and Bluetooth, has created a need for a standard solution that will enable Bluetooth technology to mitigate other interferences in its working band. This task has been assigned to the coexistence working group of the Bluetooth SIG, which has adopted the AFH as the leading solution.

The AFH is a non-collaborative mechanism, which includes a modified frequency-hopping kernel that adapts itself to the crowded RF medium by dynamically replacing frequencies within the hopping sequence. The channel replacement is based on indications from a channel assessment mechanism, which classifies each of the 79 1MHz channels as "good" or "bad" and makes a decision whether or not to exclude it from the FH sequence. The channel assessment can be based on packet error rate (PER), bit error rate (BER), received signal strength indication (RSSI), or any other applicable metric. The master can update the hopping kernel based on an assessment that it performs itself, or based on channel assessment information that it requests from its slaves. Notwithstanding, the AFH specification does not specify which method should be used for channel assessment, nor does it specify how frequently the assessments should be updated.

The AFH is most effective when the Bluetooth and WLAN radios are not collocated, and it loses its effectiveness if all the band is filled with 802.11 interference. For these reasons AFH has been found less applicable for PCA-based devices during collocated usage scenarios (i.e., when both WLAN and Bluetooth radios have to operate simultaneously). However, AFH is being supported as it forms a very useful feature for other non-collocated usage scenarios. Other methods for enabling coexistence in collocated scenarios are described later.

Extended Synchronous Connection Oriented (eSCO)

The eSCO extends the existing SCO connection by defining a new synchronous logical link, which is more reliable than the legacy SCO. The higher reliability is achieved by applying Cyclic Redundancy Check (CRC), which allows retransmissions of corrupted Extended Voice (EV) packets to each of the eSCO packets. The new mechanism adds three new packet types: EV3, EV4, and EV5, which are defined with regards to the legacy SCO channels as follows:

EV3 = HV3 + CRC

EV4 = 3 slot HV2 + CRC

EV5 = 3 slot HV3 + CRC

The eSCO uses a separate active member address (AM_ADDR) called a logical transport address (LT_ADDR), which enables a separate automatic repeat request (ARQ) scheme to be used in parallel with the existing one that is used for asynchronous connectionless (ACL) transmissions of that specific Bluetooth mechanism. The eSCO can be used for transparent synchronous data as well as for audio. Since eSCO enables synchronous *asymmetric* links (as opposed to SCO), data rates such as 384kbps and 564kbps can be achieved. These rates match the data rates enabled by the 3G Universal Mobile Telecommunications Service (UMTS) systems. This makes eSCO most suitable for audio and video streaming applications over 3G networks. Moreover, the eSCO enables a new way to combat the audio quality degradation that results from coexistence interference in the 2.4GHz band. In addition, since it reduces the collision probability with a transmitted WLAN packet, it increases the throughput of the WLAN system (compared to usage of HV1 or HV3, [5]), so eventually both sides benefit from the usage of the eSCO feature.

Future Improvements of WPAN Radio

Future releases of the Bluetooth specification will introduce two new increased rate enhancements for the basic rate (BR): the medium rate and the high rate.

1. *Medium Rate*–The medium rate mode (MED) [13] provides a data rate enhancement targeted at usage scenarios where a 2x or 3x increase is beneficial. The rate increase is enabled by applying different modulation schemes to only the packet payload, while the rest of the payload remains modulated using the legacy 2-GFSK modulation. The MED enables gross air rates of 2 Mbps using $\pi/4$ Differential Quadrature Phase Shift Keying (DQPSK) modulation, and optionally 3 Mbps using 8 Differential Phase Shift Keying (DPSK) modulation. The achievable user data rates are up to 1.45 Mbps and 2.18 Mbps, respectively. The MED is an evolutionary extension to Bluetooth technology that is designed to operate concurrently with Bluetooth 1.x slaves in the same Bluetooth network (a.k.a. piconet). It reuses most of the existing Bluetooth 1.1 and 1.2 functionality and requires a major change only in the PHY layer. In addition, there will be further minor changes in the Link Manager (LM) and Host Controller Interface (HCI).

2. *High Rate*–The high rate (HR) [11], [12] is a proposal for Bluetooth 2.0 that combines new MAC and PHY layers. The HR aims at achieving data rates that are 10 times higher than the rates enabled by the BR. The new MAC layer introduces the idea of a token-based distributed MAC, supervised by a single device called a “supervisor.” The role of the supervisor is mostly to facilitate fair token distribution among the network peer devices. This concept is proposed in order to reduce the relatively high latencies and overhead imposed by the centralized MAC scheme that is used in the 1.x Bluetooth mechanisms.

   The air interface of the HR is the second dramatic change introduced by the new standard. The most important thing to notice is that the HR channel does not frequency hop. Instead, it statically occupies a 4 MHz channel (5.6 MHz@-20dB). The optimal HR RF band is chosen via a dynamic channel selection (DCS) mechanism, which picks up a carrier out of a set of 70 possible, 1 MHz separated, RF carriers. This new air interface introduces an inherent coexistence problem with legacy Bluetooth mechanisms, similar to the one introduced for example, by 802.11. However, the HR specification proposes to tackle this problem by applying the AFH scheme in the legacy FH systems.

   The HR baseband uses an adaptive modulation scheme of M-ary phase shift keying (PSK) differential modulation with a symbol rate of 4 Msymbols/s. Three types of modulation schemes (which can be adapted according to QoS requirements and channel conditions) have been defined as follows:

   - 8-DPSK - 12 Mb/s
   - 4-DPSK - 8 Mb/s
   - 2-DPSK - 4 Mb/s

Finally, Table 1 summaries the main features of the two new radio enhancements of the Bluetooth specification. The table compares the MED and HR in terms of data rates, control, MAC method, Data Link Control (DLC) methods, and Radio Resources Management (RRM) methods.

Table 1: Comparison of medium and high rate

	Medium rate	High rate
user rates (Mb/s)	0.7, 1.4, 2.1	3.8, 7.6, 11.4
control	Centralized	distributed
MAC	Polling	token
DLC	Packet	segment
RRM	FH	DCS

The introduction of the HR might bring up again the debate about the need for Bluetooth technology in parallel with Wi-Fi networks. Nonetheless, the HR should be considered only as a natural evolution of the WPAN, which complements the Wi-Fi technology. The HR is proposed as an optional extension, not a replacement for the Bluetooth 1.x and is designed to live concurrently with the BR piconets. In summary, HR addresses the increasing need for high-speed cable replacement and reliable applications such as high-quality audio and video gaming.

Bluetooth Profile Advancements and Trends

Much of the success of Bluetooth technology in the last couple of years should be credited to its wireless audio applications—the headset and hands-free devices. This trend towards wireless audio devices, powered by the automotive industry and consumer demand, has led to the development of advanced profiles for enhancing the audio quality and increasing the range of applications that can be supported by such devices. New headset designs being released offer, besides a cool shape, an increased talk-time with enhanced audio quality, which are enabled by these hands-free profiles (HFP) and headset profiles (HSP). The dramatic improvement in the audio quality is achieved by incorporating digital signal processors (DSPs) and algorithms for echo cancellation and noise suppression in the headset design, and by using the 1.2 new features such as AFH and eSCO for mitigating local interference.

More and more headset designs are being based on the HFP, which is slowly taking the place of the HSP. The HFP enables not only basic audio connectivity, but also mobile phone remote-control capabilities and is applicable to both headset devices and car-kit hands-free systems. Another profile that extends the HFP features is the phone access profile (PAP), which enables full remote control of the mobile cellular phone through a car phone.

The additional processing power provided by DSPs in the headsets enables advanced profiles such as the advanced audio distribution profile (A2DP), which defines the protocols and procedures that are used to implement distribution of high-quality audio content in mono or stereo (e.g., MP3) on ACL channels. These improvements are geared towards increasing the market penetration of mobile phones enabled with Bluetooth technology.

The Personal Area Networking Profile

The Bluetooth SIG Personal Area Networking (PAN) Working Group (WG) has defined a new protocol and profile to enable existing networking applications to work over Bluetooth links by using existing networking protocols such TCP/IP. The new profile is called the Personal Area Networking (PAN) profile. The Bluetooth SIG defines profiles to specify how devices should use various protocols to ensure interoperability between devices supporting these profiles. In addition to the PAN profile, a specification for a new protocol called Bluetooth Networking Encapsulation Protocol (BNEP) has been developed. The BNEP specification provides an "Ethernet-like" layer in which existing networking applications can function over Bluetooth links without any additional changes.

The PAN profile brings a rich networking environment to devices enabled with Bluetooth technology and explodes the usage of these devices. The PAN profile, along with BNEP protocols, aims to provide an Ethernet-like networking infrastructure for devices enabled with Bluetooth technology. Hence, the PAN profile opens a huge window for Bluetooth products to incorporate TCP/IP-based protocols and applications seamlessly. Essentially, the PAN profile makes the Bluetooth mechanism an integral part of a network that provides the user voice and data on the go.

There are many other profiles that are geared to support printers, audio, and video usage models; they are not addressed or described in this paper.

Ultra Wideband

Ultra Wideband (UWB) is a high-speed, low-power, wireless technology designed for distances less than ten meters. The IEEE 802.15 task group (TG) 3a [6] was formed in early 2003 and is working on defining a specification for a UWB physical layer for the IEEE 802.15.3 protocol. Currently, the IEEE 802.15 TG3a WG is evaluating proposals against their functional requirements criteria. The IEEE 802.15 TG3a requires data rates of 110 Mbps or faster and will have Quality of Service (QoS) support focusing on supporting high-rate multi-media. As the UWB standardization effort progresses so will its importance as a WPAN technology.

Internet Engineering Task Force Mobility Drafts

During the past several years the Internet Engineering Task Force (IETF) has been working on defining protocols to enhance mobility. One protocol in the final stages is Mobile IPv6 [7]. Mobile IPv6 defines a mechanism as something that allows a mobile device to maintain the same IP address as the mobile device moves around the Internet. By maintaining the same IP address, the application will continue to function and maintain all networking connections. This capability allows mobile hosts to move from network to network and switch networking technologies, while maintaining network connections. There are many other IEFT drafts that improve the capabilities of mobile nodes as they move throughout the networks [8].

Java Specification Request - 82

JSR-82 is a Java Specification Request that was issued in 2002 by an expert group chaired by Motorola with additional members such as Rococo Software, Ericsson, Nokia, and others. Its goal was to standardize a set of APIs to allow Java technology-enabled devices to be integrated into a Bluetooth environment.

The JSR-82 specification was defined for the target platform of Java* 2 Micro Edition (J2ME). The J2ME is a subset of the Java 2 platform technologies and is optimized for portable devices such as PDAs and mobile phones. The J2ME is composed of two modules: Configuration and Profiles. The Configuration module provides the minimum set of classes and virtual machine (VM) features that must be present for a particular set of devices. The Profiles module, which is layered on top of the Configuration module, provides the application developers APIs for a particular set of devices. In the context of mobile phones, the Configuration module is called the Connected Limited Device Configuration (CLDC), and the Profile module is called the Mobile Information Device Profile (MIDP). The CLDC provides a fast, small footprint virtual machine (called a KVM) and a stripped-down Java API subset. The MIDP provides a set of user interface components, a persistence mechanism, and a Hypertext Transfer Protocol (HTTP) connection capability.

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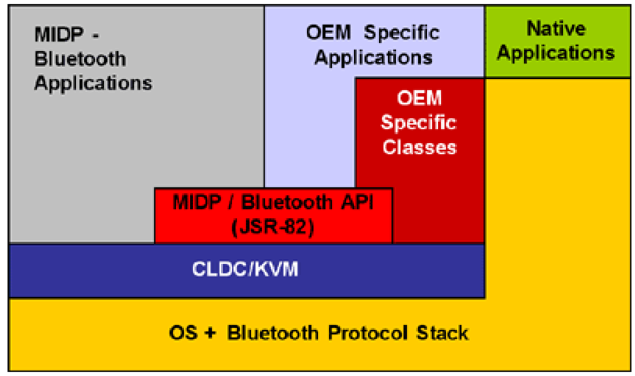

Figure 3: JSR-82: CLDC+MIDP+Bluetooth software architecture

The JSR-82 API provides support for only four fundamental Bluetooth profiles including Generic Access Profile (GAP), Service Discovery Application (SDAP), Serial Port Profile (SPP), and Generic Object Exchange (GOEP), and it has limited access to the stack for Bluetooth radio control. Some basic functionality, such as SCO connection establishment, or resetting the Bluetooth radio, etc., has been excluded and is not being supported by the JSR-82 API. The software architecture of a system enabled with JAVA and Bluetooth technology that supports the JSR-82 is described in Figure 3.

To summarize, the JSR-82 opens for the PCA a new dimension for peer-to-peer networking applications, such as multiplayer wireless games in which users can interact with each other over the Bluetooth link, or interact with a central "data kiosk" for gaming or information-downloading applications.

CHALLENGES AND SOLUTIONS FOR PLATFORM AND HANDSET INTEGRATION

Integrating multiple wireless technologies in Intel Centrino mobile technology and Intel Personal Internet Client Architecture (PCA) creates several challenges. This section of the paper focuses on Wireless Personal Area Network (WPAN) integration for the Intel Centrino mobile technology and PCA platforms.

Bluetooth Integration Considerations in Notebooks

Hardware Integration

Bluetooth specifications define various interfaces that can be integrated with the main system. They are as follows:

- Universal Asynchronous Receiver Transmitter (UART): Bluetooth radio is integrated using a UART connection on the same printed circuit board (PCB) as the main system. This is the preferred method for most hand-held devices, since it provides cost-effective solutions.

- Universal Serial Bus (USB): Bluetooth radio is integrated as a USB client device. This is a *de facto* standard for mobile PC platforms.
- Card Bus: During the initial stages of Bluetooth development, many vendors provided Bluetooth radio as an add-on card for mobile PC platforms.
- Peripheral Components Interconnect (PCI)-Express: In future mobile PC platforms, one can expect usage of the PCI-Express to be integrated into Bluetooth radio. The PCI-Express offers better power management, software compatibility, and lends itself to integration into the Bluetooth radio on the back lid of a mobile PC platform. Studies have found that integrating a Bluetooth radio on the lid offers superior radio frequency (RF) characteristics.

Power Management Design Considerations for Mobile PC Platforms with an Integrated Bluetooth Radio

Extending battery life is an important objective for the Intel Centrino mobile PC platforms. On Centrino platforms, USB has become a *de facto* standard for integrating a Bluetooth radio on the platform. USB supports multiple techniques of low-power modes. Due to current limitations of the platform, USB selective suspend has become a preferred mechanism for the power management of the Bluetooth radio. In this method, the Bluetooth USB driver suspends USB transactions, when the Bluetooth radio is idle for a few seconds. This allows the PC processor to go into low-power mode, thereby saving battery life significantly.

Wake on the Bluetooth host controller will become one of the key features for future mobile PC platforms. This feature allows a USB-based Bluetooth radio to wake up the mobile PC from the standby mode. The feature provides additional battery savings, while providing the ability to respond to external Bluetooth host controller events. The Bluetooth specification provides a facility for setting up multiple event filters on the Bluetooth radio by the host. Typical event filters are *event* on Bluetooth connection from a specific Bluetooth unit and *event* on paging from any Bluetooth unit. To support Wake on the Bluetooth host controller, the host processor typically sets some event filters before going to standby mode and then goes to standby mode to save battery energy. In this scenario, Bluetooth radio is still powered and wakes the system when it recognizes a particular event that matches the set event filters.

SW Structure—Protocol Stack, Profiles and Applications

Specification of the Bluetooth system defines a layered software structure covering radio baseband systems, link layers, higher level protocols, and application profiles.

Bluetooth radio chip vendors provide baseband support and export the standard HCI interface. Operating system (OS) vendors and application vendors implement the rest of the software stack and applications, which run on the host processor.

In some cases, Bluetooth radio chip vendors are implementing application-level profiles such as Serial Port Profile (SPP) on the chip itself. In this case, the Bluetooth radio acts like a wireless serial port and enables legacy systems without requiring software changes on the host.

An application with Bluetooth wireless technology operates in a wireless environment unlike a typical application that operates in a wired environment. This wireless scenario forces the application to discover other Bluetooth products and services and connects to them securely before exchanging data. The Bluetooth SIG defined a number of profiles to enable service discovery, authentication, and various data transfer mechanisms.

The usage of various profiles can be explained by enumerating a typical conversation between two Bluetooth products.

A Bluetooth product uses a Service Discovery Application profile (SDAP) to discover services offered by nearby willing Bluetooth products. If these Bluetooth products are personal devices, a user can pair them using a Generic Access Profile (GAP) thereby placing significant security barriers for other Bluetooth products to pass. GAPs provide access definitions for establishing basic link-level connections between the devices. The devices can enter into a data transfer phase by using a Serial Port Profile (SPP), which was intended to provide a basic cable-replacement mechanism that turns a Bluetooth product into a wireless serial port. Using this cable-replacement mechanism, the applications can exchange data between the devices.

Current mobile PC platforms with Bluetooth technology support Generic Object Exchange profiles for image transfers, exchanging and synchronizing Personal Information Manager (PIM) information and dial-up network profiles to establish a dial-up connection using hand-held devices enabled with Bluetooth wireless technology.

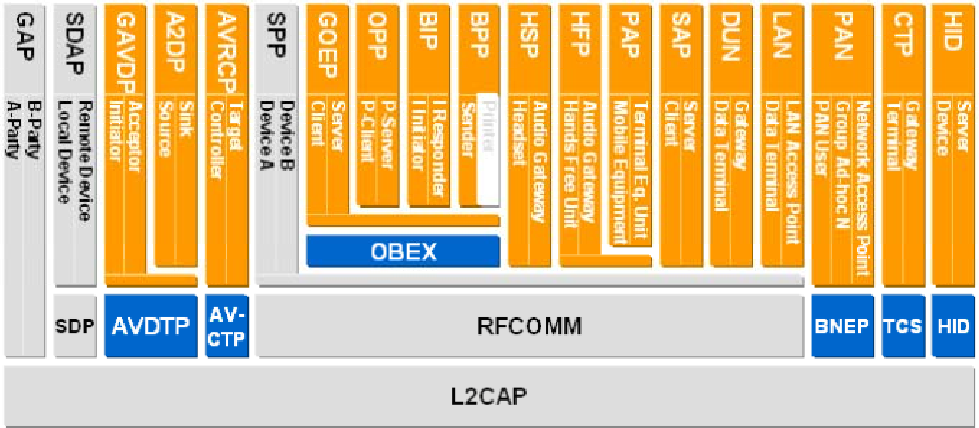

Figure 4: Mobile phone Bluetooth Software Stack and profiles (courtesy Ericsson Technology Licensing AB)

The Bluetooth Human Interface Device (HID) profile addresses usage of wireless keyboards, mice, joysticks, and remote controls based on Bluetooth wireless technology, and it uses the same HID definitions that are defined in USB HID devices. This enables usage of existing HID class drivers of mobile PC platforms, thereby speeding up implementation and adaptation of HID devices that are based on Bluetooth technology.

Further Bluetooth Integration Considerations in Mobile Handsets

The integration of Bluetooth capability into mobile handsets has evolved dramatically since the technology was introduced back in 1998. In its early models, Bluetooth technology was available only as an external dongle or as a sliding card; today, the integration is internal to the printed circuit board (PCB) either as an external single chip, or as an external module comprised of separate baseband and RF chips. In addition, a growing number of cellular and application processors integrate Bluetooth technology baseband capabilities into their silicon.

Today, Bluetooth technology capabilities can be found in a wide variety of mobile handsets and hand-held devices. The main differences between those devices (at least from the Bluetooth wireless technology perspective) are in the set of supported Bluetooth features stemming from the audience for which these phones are targeted. Roughly, we can divide the handsets enabled with Bluetooth wireless technology into four categories: low-end phones, youth phones, feature phones, and smart phones, respectively. Low-end phones usually provide only basic Bluetooth connectivity and therefore support only the headset profile (HSP), some object exchanging capability using the Object Push Profile (OPP) for business card exchanging, and basic printing capabilities using the Basic Printing Profile (BPP). Youth phones interact mainly with multimedia and gaming devices. Their supported profiles therefore focus on multimedia applications such as BIP and A2DP. Feature phones are phones that are intended mainly for professionals and gadget fans. These phones are typically showcases for almost all Bluetooth wireless technology functionality which includes all the profiles seen in Figure 4. And finally, smart phones are a mix of a traditional mobile phone and a PDA. These phones typically support operating systems such as the Microsoft* WinCE* Smartphone* 200x, Symbian*, Linux* and such, and provide Bluetooth wireless technology connectivity that is similar to the one enabled by the feature phones.

The differences in the form factor between mobile computers and hand-held devices impose several design constraints, which may be more relaxed when Bluetooth technology is integrated into mobile computers. The parameters to which special attention should be given include

- *Hardware Interfaces*. When Bluetooth wireless technology is integrated as an external chip (set), the required interfaces include a host controller interface over UART (H4) or a USB (H2), pulse-coded modulation (PCM) for audio. Each of these interfaces consists of four lines. In many cases the UART (H4) is preferable due to the relaxed requirements it imposes on the hardware. It should be noted, however, that UART is not applicable when medium-rate mode (MED) and high rate (HR)

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are considered, as it can support only limited data rates, which do not meet the data-rate requirements of the new higher rate radios. Notwithstanding, currently no definitions for new transport layers have been published by the Bluetooth SIG, although USB seems to be a natural candidate.

- *RF Interface*. This issue is mostly applicable when Bluetooth technology baseband IP is integrated into silicon, although it can also be considered as an issue when Bluetooth technology is integrated as an external chipset, composed of a separate baseband and RF chips that come from different vendors (an option which is less popular today). The chip design must then include an interface to an external RF module. Currently, there is no standard interface protocol between the Baseband IC and the RF unit defined in the Bluetooth specification. However, some Bluetooth Working Group members (Ericsson, Nokia Mitel, Intersil, and Philips) have prepared the BlueRF specification for a standard interface between Baseband and RF. An 8-line interface is required for a bidirectional port, while a 14-line interface is required for a unidirectional port.
- *Electrical Compatibility.* When choosing an external Bluetooth host controller, attention should be given to the electrical compatibility of electrical levels, polarity, protocol, and timing between the host and the Bluetooth controller. As an alternative, level-shifting devices may be used for fixing the electrical mismatches, with the drawback of increased Bill-Of-Materials (BOM) and PCB area.
- *Power Management.* Power management presents a major design challenge especially in hand-held device design, due to the smaller battery size that can be considered in such devices, which directly affects the standby and talk time of the device. The UART H4 protocol does not have a data-recovery mechanism, which makes it unsuitable for reliable communication that involves low-power/sleep periods. Data that are sent while the receiving party is asleep are lost. Furthermore, since data are being sent over UART as a stream of bytes, there is no indication as to which of the bytes has been lost. Since the 1.1 release of the Bluetooth specification did not include a standard definition for power management over UART-H4, most commercial Bluetooth chipsets available today rely on proprietary solutions that may vary from one vendor to another. The drawback of these solutions is that they are usually based on additional pins that need to be allocated for acting as wakeup pins for the Bluetooth host and Bluetooth host controller. There is a definition for a new standard (that is not part of the Bluetooth 1.2 specification), called a 3-wire HCI (H5), which, as implied by its name, consists of only 3 lines of the UART interface: TX, RX, and GROUND. The 3-wire HCI implements a protocol stack based on the Serial Line Internet Protocol (SLIP). The SLIP, which is layered on top of the UART driver, is used for transforming the unreliable flow of data bytes over the UART, into a reliable flow of data packets. The H5 defines a data-recovery mechanism as well as a hand-shaking protocol in software that enables bidirectional power management between the host and the Bluetooth host controller over the 3 UART pins. The power-management feature requires that the RX line on each side have the capability of being configured as an asynchronous interrupt line that could wake up the receiving party. In summary, the advantage of H5 for power management is in the saving of the two extra UART pins that are used for flow control (Request To Send (RTS) and Clear To Send (CTS)). The drawback of using it is the requirement for major modifications in the host controller interface (HCI) software and firmware, including the implementation of an additional protocol stack for the UART.

  As mentioned earlier, an alternative solution for the power-management problem is to use the HCI over USB (H2) specification [1], which does include standard interface lines for power management. The main drawback of using USB is the requirement for an implementation of USB host module in silicon, which is considerably more costly and complex than UART H4 silicon implementation.
- *Clocking.* Using a common clock for the entire system (Bluetooth, APPS, COMM, etc.) is desirable for many reasons, including reduced BOM, reduced power consumption, and the ability to control the Bluetooth clock by using a power-management chip. However, in mobile handset Bluetooth applications that involve audio connections such as HSP and HFP, the requirement for a common clock becomes even more critical, as the entire audio path (the audio codec, vocoder, echo canceling, noise suppression, etc.) is synchronized with the cellular base station reference clock. Using a separate clock for the Bluetooth host controller, which is not being tracked and corrected (compared to a VCTCXO clock, for example), would result in an accumulated timing drift error in the sampling time, and this will cause an annoying “clicking” sound to be heard at the near and far ends of the audio link.

CHALLENGES AND SOLUTIONS FOR MOBILE WIRELESS PLATFORMS

There are many challenges for wireless platforms and these challenges are significantly increased with multiple wireless technologies. Theses challenges range from low-level hardware issues such as platform designs to high-level issues that affect applications software. In this section we discuss some of these potential challenges and suggest possible solutions.

Wireless Security

With wireless connectivity, mobile devices are vulnerable to many additional security threats as compared to devices with wired connections. With the use of wireless networks, all data exchange via a wireless connection should be encrypted to prevent others from gaining access to that information. Encryption may be supported in several layers of the device's communication stacks. Both 802.11 and Bluetooth support encryption over the wireless link and should be used. Additionally, wireless devices, which connect up to public networks, should use Virtual Private Networks (VPNs) when connected to those networks. VPN encrypts communications from the source to the destination to prevent others from gaining access to that information as it travels the Internet.

Moreover, wireless mobile devices are vulnerable to attacks in which others may try to gain access to the mobile devices or effect their operation. Due to this threat, mobile devices should implement firewalls and other mechanisms to limit unauthorized access to the mobile devices.

Roaming

As wireless devices move from place to place, they change the location of network connectivity. As this happens the Internet Protocol (IP) address may change. The IP address is used by the Internet to deliver network communication to the correct device. Applications use IP addresses to share information across the Internet. If the IP address changes, then applications may be prevented from sharing information. One possible method to solve this issue is to use Mobile IP. With Mobile IP, the mobile device uses its home IP address for its home network as the destination for all communications. When the mobile device is at its home network, it receives all of the communications directly. When the mobile device moves away from its home network, it gets a new IP address from the visiting network and tells a device called the Home Agent (HA) what the new visiting IP address is. The Home Agent redirects network communication from the mobile devices home network to the new visiting IP address. This allows applications on other devices connected to the Internet to always use the mobile device's home IP address in order to communicate with that device. This allows users and their applications to maintain network communications as the mobile device moves from network to network.

Quality of Service (QoS)

Wireless networks are typically shared with all of the users in an area. That area depends on the technology; for example, a typical range for networks is 10 meters (m) for WPANs, 100m for WLANs, and 1000m for WWANs. Due to the sharing of the network, users may not get enough network bandwidth for their applications. Many of today's network bandwidth is shared without any guarantees. QoS mechanisms allow devices to request a guaranteed amount of access to the network. QoS mechanisms guarantee different network parameters such as data rate and latencies. By having QoS, applications can request the QoS parameters needed for their application and have a good user experience.

Bluetooth Wireless Technology Coexistence

As described in the introductory sections, the technologies that can enable the dream of "anywhere, anytime connectivity" impose the integration of cellular/Wireless Wide Area Networking (WWAN) such as GPRS, EGPRS or W-CDMA, Bluetooth technology, 802.11 WLAN, and GPS on a single platform. Side by side with the advantages that are enabled by an integration of multiple wireless technologies, such as greatly enhancing connectivity to the enterprise Intranet and the Internet and to peripherals such as PDAs, printers, and headsets, simultaneous operation of collocated radios in hand-held or mobile computer platforms presents significant design challenges. The main challenges are as follows:

- Spectral overlapping: The operation of 802.11b/g and Bluetooth technology in the same ISM band causes inevitable transmission collisions and results in QoS and throughput degradation.
- TX Out of Band: This is noise generated at the TX band of one system that increases the RX noise floor of the other system.
- Blocking: This phenomenon is caused by a strong TX signal that overloads the RX front-end.
- RX phase noise: This noise is generated by the local oscillator causing a mixing of TX signals into the RX band.
- Inter-modulation Interference: Inter modulation is caused by the collocated existence of multiple radios generating undesired inter-modulation frequency products that need to be filtered.

- Frequency planning: Careful frequency planning will ensure that frequency source harmonics don't fall in the wrong bands.
- Small factor platforms: The small form factor (especially the one that is considered in mobile phones and hand-held devices) means that several radios may share the same antenna, which can result in limited isolation between antennas.

The design challenges mentioned above are true for both mobile notebook computers as well as for hand-held devices or mobile phones. Hence, the following methods for handling and eliminating undesired RF effects apply to both designs.

Mitigating the effects of TX Out-of-Band noise, blocking, or RX phase noise is usually accomplished by adding filtering at the TX side of each of the collocated RF systems. The price for additional filtering is increased BOM and PCB size, and the insertion loss. In addition, the filtering influences the noise figure (NF) and thus the overall performance. Therefore, careful design tradeoffs have to be made.

Inter-modulation effects can be handled by using more linear devices (at the expense of higher current consumption and cost), or by using additional filtering in the RX side, which affects cost, size, and insertion loss. Using common frequency sources (if possible), additional shielding (which increases the size and cost), or robust conversion schemes, such as direct conversion radio (DCR), may offset the undesired effects of frequency planning.

Up to this point we have reviewed the design guidelines, which are common to both platforms. Yet, there is a difference in the solution approaches between hand-held and mobile computer designs. The main issues that should be taken into account are the form factor and the usage models.

Firstly, the form factor affects the antenna design. A small form factor implies that the antennas will be closer together, which results in limited antenna isolation. In addition, Bluetooth and WLAN radios may share the same antenna, which requires a time-sharing mechanism between the systems as well as tighter design of RF switches and RF terminators to prevent TX energy from leaking into the other system's receiver.

Secondly, the form factor limits the size of the batteries that can be used in the design, thereby implying tighter power-management designs for hand-held devices, as well as tighter requirements for the WLAN design.

The usage models that are considered for mobile notebook computers and mobile phones are also different. As an example, consider a phone call using a Bluetooth headset while data are being streamed over a WLAN connection. Since the audio connections over the Bluetooth headset use reserved time slots for transmission, simultaneous WLAN transmissions in those epochs can greatly reduce the Bluetooth audio quality. The usage of GPS is another example that is unique to hand-held devices; it doesn't apply to mobile notebook computers.

In the next sections we discuss solutions for coexistence that are unique to each of the platforms, separately.

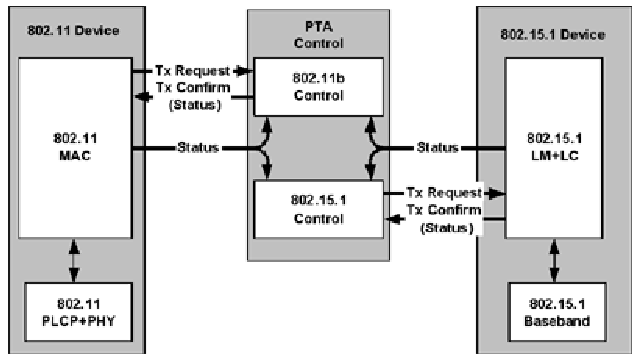

Figure 5: PTA collaborative mechanism for coexistence of 802.11b and Bluetooth technology

Coexistence Solutions in Mobile Handset Design

The integration of GPS in mobile handsets even without the presence of Bluetooth technology and WLAN is challenging, as the design of GPS receivers relies heavily on received noise levels. Higher noise levels require longer detection periods. Furthermore, GPS receivers are not designed to ignore noise bursts. Most of the existing GPS designs did not consider noise due to collocated RF transmitters. Handling such interference requires a change in the design of the receiver: tighter RF design and longer detection periods will be required. In addition, some GPS solutions will not work with a GSM interference of more than -25 dBm, and the performance of most of them starts to degrade at -35 dBm.

The coexistence of Bluetooth technology and WLAN in the same device is perhaps the most complicated of all the coexistence combinations that can be considered inside a hand-held device. Once the requirement for Bluetooth-802.11 coexistence was raised, task forces inside the Bluetooth SIG and the IEEE (IEEE 802.15.2) have been formed to propose standard solutions for the problem. Several collaborative and non-collaborative mechanisms have been proposed for enabling coexistence between 802.11b/g and Bluetooth technology [4], [5]. As mentioned previously, non-collaborative mechanisms, such as the AFH, have been mainly proposed in order to mitigate interferences in the 2.4 GHz range, rather than enabling coexistence in a collocated scenario. Using AFH solely in a hand-held device will not enable handling a voice conversation using a headset enabled with Bluetooth technology with the required sound quality, while 802.11 is trying to upload a packet. These kinds of scenarios that combine audio and data are the essence of the PCA architecture. This requirement impinges on the usage of collaborative techniques, such as Packet Traffic Arbitration (PTA), described in Figure 5, for enabling 802.11 and Bluetooth technology to coexist. PTA uses a "control entity" with the ability to control both the 802.11 and Bluetooth MACs. The control entity acts as a "traffic cop" and implements a hand-shake mechanism with both MACs in order to authorize transmissions in a time multiplexing manner. The decision algorithm gives priority to either Bluetooth or 802.11 according to the transmission type: synchronous audio transmission (SCO or eSCO) may be given priority over 802.11 data traffic. Other data packets may be permitted on a Quality of Service (QoS) basis or on similar decision mechanisms.

The implementation of the controlling entity can be done in many different ways and depends on the specific design. In an external integration of a Bluetooth host controller and WLAN, one option is to use discrete control lines to connect the MACs of the Bluetooth controller and the WLAN to each other. This can usually be implemented using two lines. The air manager can be implemented on either the Bluetooth controller or the WLAN, depending on which of the two has spare processing power for the job. Another option is to connect both MACs to the host (e.g., APPS processor) and implement the air manager inside the host processor. The drawback to this is an increased latency (due to the OS response time to hardware (HW) interrupts) and an increase in the host processor pinout (or in other words, less general-purpose input/output (GPIO) pins for other applications).

Due to the above reasons, a conspicuous market trend points towards collaboration between Bluetooth technology vendors (e.g., Silicon Wave) and WLAN vendors in order to provide a complete integrated solution for Bluetooth-WLAN coexistence. These solutions focus on providing not only a coexistence solution, but also an efficient WLAN design, from the power-consumption perspective, due to the strict power requirements for the design of hand-held devices. Nonetheless, even though those solutions require an air manager to be implemented into the design of Bluetooth-WLAN products, some derivative of an air manager implemented in the host may be required for enabling coexistence with GPS as well.

Radio Frequency Challenges in Mobile Notebook PCs

Antenna designs for notebook PCs are challenging, as generally these kinds of platforms consist of many metallic components such as framing structures, hard drives, and displays. Those can greatly distort the antenna radiation patterns, thereby causing potentially significant RF performance variations, as the notebook PC's physical orientation is varied relative to the location of the intended communicating device such as an access point (AP), a peripheral such as a printer, and even another notebook PC.

Yet, the biggest coexistence design challenge which the system designers are facing is the enabling of coexistence between the technologies of Bluetooth and 802.11. The Intel Centrino mobile technology includes the Intel Wireless Coexistence System (Intel WCS), which significantly mitigates the interference between 802.11b and Bluetooth technologies.

Intel Wireless Coexistence System

While antenna isolation somewhat mitigates interference between 802.11b and Bluetooth radios, performance is still impacted to some degree. For example, 802.11b data throughput is degraded by Bluetooth interference, even with 40dB of antenna isolation. To further mitigate interference between the Bluetooth radio and 802.11b, Intel WCS [18] was developed as one of the Intel Centrino-enabling technologies. Intel WCS, described in Figure 6, consists of a combination of antenna isolation techniques, a channel exchange, and priority signaling between an Intel PRO/Wireless Network Connection 802.11 solution and a third-party Bluetooth module. Phase 1 of Intel WCS has been implemented: it mitigates Bluetooth interference and restores 802.11b data throughput nearly completely.

Intel WCS is designed to complement the Adaptive Frequency Hopping (AFH) interference mitigation algorithm being developed by the Bluetooth Special Interest Group (SIG). AFH will mitigate the impact of 802.11b on Bluetooth data throughput, but only between AFH-compliant Bluetooth products.

Phase 2 of the Intel WCS will add Bluetooth priority signaling from the Bluetooth module to the Intel PRO/Wireless network connection, resulting in a restoration of connection reliability for both AFH and non-AFH (legacy) Bluetooth modules.

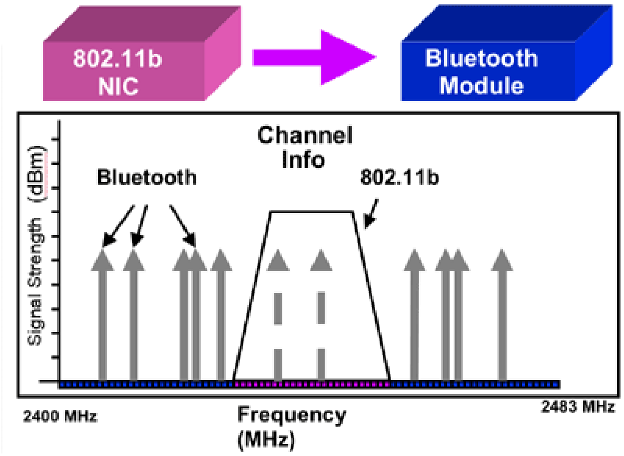

Figure 6: Intel WCS channel exchange

Multiple third-party Bluetooth silicon and module vendors have been enabled to be compatible with Intel WCS, including SiliconWave and Cambridge Silicon Radio. Extensive verification and validation testing has been completed with these silicon vendors, providing a pre-validated system solution to the customer.

In summary, integrating multiple RF technologies into mobile notebook PCs provides new challenges to systems designers, including antenna gain uniformity and interference mitigation. Intel WCS, an Intel Centrino mobile technology, provides powerful interference mitigation between 802.11b and Bluetooth radios and enhances AFH.

SUMMARY

Intel Centrino mobile technology and Personal Internet Client Architecture (PCA) are advanced communication platforms with multiple wired and wireless technologies. With these rich communication technologies, these platforms can be used for many new usage models. Many of these new usage models involve the interaction of Intel Centrino mobile technology and the Intel PCA. Additionally, some of these new usage models are enabled with the use of both the Wireless Local Area Network (WLAN) and the Wireless Personal Area Network (WPAN) wireless technologies. Many new technology innovations have enabled these usage models, and the innovations have been achieved by the use of industry standards to ensure interoperability. For multiple wireless technologies, we discussed in detail suggested methods for integrating these technologies into the platform and talked about how to deal with coexistence issues.

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