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Guest-editorial

Broadband Wireless

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1. Introduction

This special issue of the *Journal of High Speed Networks* deals with an issue of significant current interest – Broadband Wireless. A very significant research effort is underway, both in the academia and industry, to increase the bandwidth available over wireless networks. Many of the application scenarios that will drive the 'wireless Internet' are predicated upon the availability of higher bandwidth. In popular discussions, broadband wireless is often equated with 3G/4G type solutions that provide high bandwidth wide area connectivity via cellular telephony networks. The articles in this issue however go beyond such narrow constructions of the term, and examine various research issues related to broadband wireless technology. We present perspectives from both academic researchers (from UIUC and Georgia Tech) and industrial researchers (from Nokia and IBM).

The paper by Eklund et al. discusses how millimeter wave point-to-multipoint systems can be used to provide high bandwidth wireless links that are optimized for IP traffic to homes/offices. They discuss issues related to standardization, regulation, system design, and service requirements. The paper by Gao et al. addresses the issues related to improving the performance of fair queuing techniques for wireless channels by using adaptive FEC and ARQ methods. Broadband access brings with it issues relating to guarantying Quality of Service to applications. This issue is addressed in the paper by Toh and Tsai, who examine how QoS mechanisms in wireless ATM systems differ from their wired counterparts. In terms of short range personal area networks, the use of RF has yielded significantly higher speeds than Infrared systems. Bluetooth is one of the leading standards in this area, and the paper by Kumar et al. examines algorithms for scheduling and queuing issues in Bluetooth Systems.

In summary, the four articles that form this issue bring out interesting work in some important and hard problems related to broadband access in its various forms. While Bluetooth technology is only one of the issues discussed in this issue, we'd like to devote some of the editorial to give you more information about it, given its importance and timeliness. We were helped in writing this by Filip Perich and Jeffrey Undercoffer of the Department of Computer Science and Electrical Engineering, University of Maryland, Baltimore County, and by Chatschik Bisdikian of the IBM T.J. Watson Labs.

2. Bluetooth

The Bluetooth wireless technology aims in uniting personal computing devices into a collaborative, interconnected electronic community. Its name is derived from the 10th century Danish king Harald Blåtand (Bluetooth) who united Denmark and Norway. In February 1998, Ericsson, IBM, Intel, Nokia, and Toshiba formed the Bluetooth[1] Special Interest Group (SIG) and agreed to work on the development of an international communications standard that will simplify interactivity between personal devices by eliminating connection cables and enabling personal area networking. As of early this year, the SIG has grown to nine promoters (the previous five plus 3Com, Agere, Microsoft, and Motorola) and over 2100 adopters including all sorts of industrial, scientific, and educational institutions. It is a cable replacement technology but also much more. It is an enabling technology, defining profiles for object exchange, service discovery, wireless telephony, and serial applications such as LAN access, fax and networking. It seeks to couple the usability models provided by different devices. An example is coupling the functions of a PDA with that of a cellular telephone. At first blush this might be viewed as a simple convenience, one where a telephone number contained in the PDA can be sent to the mobile telephone. However, more generally, it opens doors to innovative applications by allowing any nearby phone to serve as a communications portal for the PDA.

2.1. Technical

The current Bluetooth specification is Version 1.1 and was released in early March 2001. Prior to Version 1.1 implementations of Bluetooth, specification Version 1.0b was used, which was easy to misinterpret, particularly at the lower levels of the protocol stack where devices communicate with each other. The implementation variances were particularly noticeable at the April 2001, CeBit trade fair in Hanover, Germany, when 100 Bluetooth devices failed to provide an inter-connection between each other.

The Bluetooth protocol stack can be divided into three groups of protocols as shown in Fig. 1.

1. The *transport communication protocols group*: It comprises a set of Bluetooth specific protocols that are present in any end-to-end communication between two Bluetooth devices. The radio specification defines a frequency hoping, spread-spectrum (FHSS) system operating in the license-free 2.4 GHz industrial, scientific, and medical (ISM) band. The specification defines a radio transmit power of up to 100 mW (20 dBm). However, a typical Bluetooth radio is expected to have a 1 mW (0 dBm) maximum transmit power. This power level would match the cost and power requirements of typical portable consumer devices like cellular phones and PDAs. The radio hops at a nominal rate of 1600 hopes per second to achieve high noise resilience. The baud rate is 1 Msymbols/sec using a binary Gaussian frequency shift-keying (GFSK) modulation technique; hence, the raw link speed is 1 Mbps. The radio hops pseudo-randomly on 1 MHz-wide channels over the 79 possible channels (accounting for the guard gaps as well) in the ISM band that occupies the frequency band between 2400 GHz and 2483.5 GHz. The Bluetooth regulatory group is working in harmonizing the frequency band assignments for the 2.4 GHz ISM band globally. As of this writing, the North American countries, the countries of the European Community, and Japan, have all agreed to harmonize their 2.4 GHz license-free band. The baseband defines the processes for devices to find, connect, and communicate with each other. It also defines low-level bit and packet level operations like error detection and correction, whitening, encryption, and so on. For Bluetooth devices to communicate with each other, they need to be members

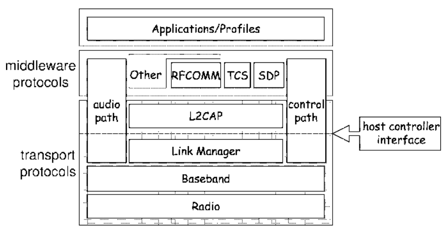

Fig. 1. The Bluetooth protocol stack.

[1]The BLUETOOTH trademarks are owned by Bluetooth SIG, Inc., USA.

of a *piconet*. The piconet comprises a well-defined sequence of frequency hops occurring in a slotted (fixed intervals) fashion over which the members of the piconet can communicate. A piconet has at least one device associated with it and it may contain up to of 8 actively communicating devices. One of the devices of the piconet, called the *master*, regulates the frequency hop sequence and timing of the piconet, and also controls the sequence of transmissions on the piconet. The remaining devices, called the *slaves*, communicate only with the master and only after the master has transmitted to them first. Thus, transmissions on a piconet occur in a slotted *time-division duplex* (TDD) fashion, with even slots occupied by transmissions from the master to a slave, and in the subsequent odd slot occupied by a transmission from the slave back to the master. The link manager and the associated protocol, the link manager protocol (LMP), define the characteristics of the Bluetooth link between devices. It defines the message exchanged for authenticating a device and enabling encryption of the link. The actual authentication and encryption algorithms are part of the baseband. The logical link control and adaptation layer and the associated protocol, logical link control and adaptation protocol (L2CAP), is a Bluetooth specific protocol through which all application data using Asynchronous Connectionless (ACL) links passes. First of all, L2CAP defines multiple logical channels multiplexed within a single ACL link. Through these logical channels, multiple applications in a Bluetooth device A can communicate to multiple applications in a device B, with each pair of applications in the two devices utilizing exclusively one of the L2CAP logical channels. Furthermore, L2CAP supports protocol multiplexing, thus allowing multiple protocols to utilize a common ACL link.

2. The *middleware communication protocols group*: It comprises a set of non-Bluetooth specific protocols as well as Bluetooth specific protocols that are used to enable new and existing applications to run over Bluetooth links. One of the initial applications for the Bluetooth wireless technology is to serve as a replacement for the ubiquitous serial cables that connect a plethora of personal devices (albeit, using different port designs for different devices). To do so, and to take immediate advantage of the myriad of applications written for interactive applications over serial cables, the SIG defined a serial port emulator called RFCOMM. RFCOMM is based on the ETSI 07.10 standard that defines a multiplexing scheme for serial communications over a common serial medium. Other protocols at this level deal with Telephony control, and discovering ‘services’ on nearby Bluetooth enabled devices.
3. The *applications group (profiles)*: Not really a communications protocol group, although it can be thought as such. It comprises a set of core applications that run over Bluetooth links that have been developed by the SIG in an effort to help in the development of interoperable applications. These applications are described in a series of specifications referred to as the *profiles* and describe how specially identified applications will use the transport and middleware communication protocols to accomplish desired usage scenarios.

Currently, Bluetooth has a transfer speed of 720 kbps, a small portion of the 11 Mbps transfer speed provided by the competing 802.11b wireless standard. However, unlike 802.11b that generally operates in an infrastructure mode, Bluetooth has the capability of forming ad-hoc networks. There are also ongoing efforts, especially in the IEEE 802.15.

From a security perspective though, its designers have not addressed the issue of a user that wants to keep his or her Bluetooth link between a device and its user interface private.

2.2. Market

Given the lack of demand for existing Bluetooth products, and the expense of those that do exist, it seems to indicate that Bluetooth does not currently have the market appeal its inventors and backers are hoping for. An informal survey of technology related news shows that few manufactures are making Bluetooth enabled devices. Current products include mobile telephone headsets, modules for interconnecting devices to a PC, and devices to link the Visor and the new Palms. For the PC market Bluetooth cards cost in the range of US$ 175–250.

According to the Bluetooth web site (www.Bluetooth.com) there are 157 qualified Bluetooth products within the following categories:

- Mobile telephone accessories
  - Headsets
  - PCS telephone
  - Phone modules
- Mobile computers
  - Laptops
- Computer accessories
  - PCMCIA cards
  - USB dongle
  - USB adaptor
  - Printer adaptor
  - Modem access point
- Computer hardware integration components
  - Protocol stack
  - Radio
  - Baseband components
- Office equipment
  - Projector kit
  - Access server
  - Headset
- Development tools
  - Software development kits
  - Protocol analyzer

Additionally, we searched for other Bluetooth products available in the marketplace. Although anecdotal, this product search disclosed few additional instances of Bluetooth products. Examples of such products that are currently being produced or were announced include:

- The ‘Waveclip’ from Sunderland Technologies, a US$ 320 device to link a Palm V to other Bluetooth-enabled devices.
- The ‘Clie’ PDA from Sony, which promises to feature Bluetooth support in July 2001.
- The Intel Personal Wireless Module, which provides both voice and data connectivity between various devices.

Currently, the utility of Bluetooth enabled devices do not warrant their price tag nor is the demand for Bluetooth products, as evident by the seemingly lack of interest at the recent CTIA Wireless show in Las Vegas, as great as Bluetooth proponents would hope for. As for corporations willing to invest capital and resources, evidence goes both ways. Microsoft Corporation – a member of the Bluetooth Special Interest Group, has announced that it will not add support for Bluetooth in its next Operating System, while Dell Corporation led a US$ 25.5 million funding round for a chipmaker to help it bring a Bluetooth-compatible chip to market.

2.3. Future research directions

The wide variety of usage scenarios envisaged for the Bluetooth wireless technology lends itself to a wide range of research areas related to the Bluetooth specification. As the Bluetooth wireless technology is driven by market needs, the Bluetooth SIG itself recognizes the need to expand its activities to fulfil market demands. Next, we outline a few research examples that point to a web of research topics focusing around the Bluetooth wireless technology.

The need to support very fast connections, in the order of milliseconds as opposed to seconds, calls for the development of faster inquiry and page processes. This may imply new inquiry and page processes within the current framework of inquiry and paging procedures, which are based on well-defined frequency hoping sequences. Alternatively, 'back' channels may be used, including the use of supplemental wireless technologies that aid in quickly identifying the device with which one wants to engage in Bluetooth communications.

Supporting richer media streams over Bluetooth links for other than voice audio, like high-quality audio and video, will require the development of more robust transmission scheduling mechanisms that will provide for increased levels of quality of service (QoS). Currently, the L2CAP layer, includes a set of QoS parameters, including the familiar leaky bucket parameters. However, there exists no mechanism to enforce any QoS contracts. Moreover, all the L2CAP logical channels between two devices are multiplexed over the single ACL baseband link between the devices. Thus, all QoS requirements for traffic flows between applications in two communicating devices need to be aggregated to a single, simple baseband parameter: transmission rate. The transmission rate of packets between two devices is regulated by the polling interval agreed upon by the devices through link manager transactions.

In a Bluetooth piconet, the network topology is that of a star. Within a piconet, a slave always communicates with the master of the piconet. Slave to slave (peer-to-peer) communication at the baseband layer are not permitted. Direct broadcasting by any slave to the rest of the devices in a piconet is also not possible. This, of course, does not mean that peer-to-peer interactive applications cannot run over Bluetooth piconets. For this to happen, one needs to device a convergence protocol layer to emulate a peer-to-peer communications environment for applications.

A closely related research topic is the support for IP communications over Bluetooth links. Note that from the point of view of the Bluetooth transport protocols, see Fig. 1, the IP protocol can be treated as an application level communications protocol. For the 'IP application' to operate properly, it needs to make certain assumptions on the capabilities of the lower layers. For example, for IP control and management, the IP application needs to assume that the underlying link layer has some form of broadcasting capabilities. These assumptions on the lower layers need to be satisfied by the convergence protocol layer mentioned earlier. Extensions on this research may be focused on extending the support for the IP application over multiple piconets, referred to as scatternets in the Bluetooth parlance. When multiple piconets are in operation in the vicinity of each other, e.g., at an airport, several of which bridge over to a wireline backbone infrastructure then the issues of roaming and hand-offs arise. These issues need to be solved within the constraints of the Bluetooth wireless technology of simplicity and power restrictions. Issues related to supporting IP communications over Bluetooth piconets are being addressed by the PAN working group within the SIG. Due to the importance of this issue discussions of supporting IP communications over Bluetooth piconets has recently started to be discussed within the IETF as well; as of this writing, no decision to formalize this discussion group within IETF has been made.

The 2.4 GHz ISM band is a heavily utilized band. Microwaves and street lamps 'pollute' this frequency band. A new generation of cordless telephones use this band as well. The ever increasing in popularity 802.11 wireless LAN technology also uses this band, as is the HomeRF technology for wireless interconnects at home. As if this is not enough, cordless telephones have started using this band because it is considered a quite enough band! It is not hard to envisage that Bluetooth and 802.11 and other 2.4 GHz ISM band technologies would be exercised at the same time by the same or different persons. For example, in the waiting room of a train station, a person may surfing the web using an 802.11 public access point, while another person close by is using the modem capabilities of her cellular phone infrastructure to connect to a data service through an invisible Bluetooth link between the cellular phone and her notebook computer.

The Bluetooth wireless technology was not designed with traditional networking in mind. The Bluetooth wireless technology is optimized to provide ad-hoc connectivity between personal devices at low cost, small footprint and power requirements. As a result, we cannot exclude the possibility of having certain mobile computing platforms that have both 802.11 and Bluetooth communication capabilities. In the presence of several 2.4 GHz technologies, the issue of interference and coexistence policies rises. Developing simple to implement coexistence procedures to allow, say, 802.11 and the Bluetooth wireless technology to coexist either in the same space, or even more, in the same device points to a research direction of the highest importance.

As mentioned earlier, the Bluetooth wireless technology is very much market driven. It has been created to address market needs. As such, in addition to the technical issues that relate to the Bluetooth transport protocols themselves, plenty of research opportunities exist focusing on end-to-end vertical solutions. For example such solutions may include how the Bluetooth wireless technology is to be used for accessing personal data in a pervasive manner; maintaining secure communications; executing financial transactions; interacting and controlling ones immediate environment; providing context aware applications; enabling new hidden computing applications, and so on. All the previous items are well within the space of Bluetooth research, without necessarily reflecting directly on the Bluetooth specification itself.

In closing this discussion, we mention the related standards activities of the IEEE 802.15 working group. The 802.15 working group is developing RF-based wireless standards for Wireless Personal Area Networks (WPANs). The 802.15.1 task group is developing an IEEE 802 standard based on the transport protocols of the Bluetooth protocol stack, i.e., the L2CAP layer and below. The 802.15.2 task group studies coexistence issues between 802.11 2.4 GHz solutions and 802.15 (and in particular the 802.15.1 standard, i.e., the Bluetooth wireless technology). The 802.15.3 task group is developing a PHY and MAC standard for high-rate ($>$20 Mbps) WPAN systems (e.g., for fast download and upload of high quality digital images to and from a personal digital camera). Finally, the 802.15.4 task group is developing a PHY and MAC standard for low-rate ($<$200 kbps) WPAN systems (e.g., for ultra low cost and power array of environmental sensors or identification tags).