BLUETOOTH AND AD HOC NETWORKING

Jari Välimäki
Networking Laboratory
Helsinki University of Technology
Email: jari.valimaki@hut.fi

Abstract

This paper is written to give introduction of the usage of the Bluetooth technology in ad hoc networking. Most common ad hoc networking applications for Bluetooth technology are introduced and current status of the Bluetooth technology suitability for ad hoc networks is examined. Also different protocols and functions, which are integral part of Bluetooth specification and used for ad hoc networking purposes, are discussed. Finally there are some recent studies shortly evaluated concerning Bluetooth scatternet formation and routing protocols performance.

1 Introduction

An ad hoc network is a network with temporary plug-in connections, in which the network devices are part of the network only for the duration of a communications session or, in the case of mobile or portable devices, while in some close proximity to the rest of the network. Ad hoc network is often local area network or other small area network formed by wireless devices. In Latin, ad hoc literally means "for this," further meaning "for this purpose only," and thus usually temporary. The term has been applied to future office, home and personal area networks in which new network nodes can be quickly added and removed. [1] The area of ad hoc networking has gathered much research interests in the past years. Many studies have concentrated on the routing issues of ad hoc networking [2].

Bluetooth is one of the technologies that can be used for ad hoc networking. Bluetooth specification is a computing and telecommunications industry specification that describes how e.g. mobile phones, computers, and personal digital assistants (PDAs) can easily interconnect and communicate with each other by using wireless transmission in a short-range. The goal of the specification is to eliminate the need for any cable connectivity and promote ad hoc networking. By using this technology, users of cellular phones, laptops, PDAs, etc. portable devices can quickly share information with each other, for example, in a conference room using ad hoc networking. [1]

The key features of the Bluetooth specification include robustness, low complexity, low power, and low cost. Bluetooth requires low-cost, down to $5, transceiver chip be included in each device. The transceiver transmits and receives in unlicensed IMS (Industrial, Scientific and Medical) frequency band of 2.4 GHz that is available globally. The technology is a combination of circuit switching and packet switching thereby supporting both synchronous voice channels and asynchronous data channels. Connections can be point-to-point or multipoint. The maximum usage range is between 10 to 100 meters with three output power classes of 1, 2.5 and 100 mW. In theory, data can be exchanged at a rate of 1 megabit per second. However, the actual maximum data exchange rate is 723 kbps. A frequency hop scheme allows devices to communicate even in areas with a great deal of electromagnetic interference within 2.4 GHz IMS band. [3] There are currently three different versions of the Bluetooth specification: 1.0, 1.0b, and 1.1. For more detailed information on Bluetooth the reader should look into *Core Specification of the Bluetooth System* [4] or *Bluetooth: Connect without Cables* [3] book.

As mentioned, the original idea of Bluetooth concept was that of cable replacement between portable and/or fixed electronic device. According to the specification, when two Bluetooth devices come into each other's communication range, one of them assumes the role of master of the communication and the other becomes the slave. This simple "one hop" network is called a piconet, and may include up to seven active slaves connected to one master. As a matter of fact, there is no limit on the maximum number of slaves connected to one master but only seven of them can be active at time, others have to be in so called parked state. [5] See Figure 1 for basic piconet topologies introduced.

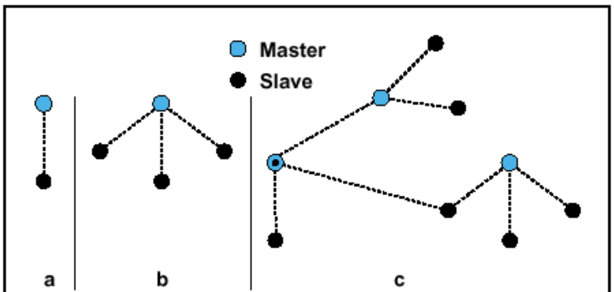

Figure 1: Piconets with single slave operation (a), multi-slave operation (b) and scatternet operation (c).

The specification also allows multiple roles for the same device, i.e. a node can be a master in one piconet and a slave in another. This permits the connection of several piconets as the nodes functioning in master/slave mode act gateways between piconets. In the Bluetooth concept the network topology resulting by the connection of piconets is called a scatternet. A node can be active in only one piconet at time, and to operate as a member of another piconet, a node must switch to the hopping frequency sequence of the other piconet. [5] Functionality and performance of ad hoc scatternets has gathered much research interest in resent years.

2 Network topologies

This chapter examines in more detail the basic Bluetooth network topologies and their usability in real life applications. There is also some comparison made against other solutions available in market and evaluated the competitiveness of the Bluetooth topologies against the other solutions.

2.1 Point to point applications

Point to point connection is the very basic functionality of the Bluetooth technology. It is not exactly the main interest of us when talking about Bluetooth ad hoc networks, indeed it can said that it is more like ad hoc connection than network. However, some key issues of Bluetooth usability in piconets with a single slave should be noted to understand how it is performing in the area where it is originally plant to be used. This helps us to understand the future availability of Bluetooth enabled devices in general.

Point to point connectivity with Bluetooth is obviously an alternative for cable connectivity. However, it is clearly not an option as replacement of every type of cable connections. The data transmission rates that Bluetooth is currently designed to support are not suitable for high capacity connections. Connections using over 723 kbps data transmission rates will most probably not be replaced by Bluetooth simply for the sake of having a wireless connection.

Computer industry is today widely supporting the Universal Serial Bus (USB) cabling standard for chaining peripherals together. Currently USB is enabling data transmission rates up to 12 Mbps. Any peripheral whose performance is less than satisfactory over such a connection is probably not going to benefit from a wireless link running at less than a tenth of this capacity. The next version of USB is expected to run at 480 Mbps with the aim of being able to support digital video. After this there is clearly even less ground for Bluetooth technology to work as a USB replacement. [6]

The same goes for the IEEE 1394 standard, also known as Firewire and iLink. This standard enables connections which runs at speed of 400 Mbps in true peer to peer fashion and are being adopted by the consumer video products industry for the likes of camcorders and as a wired networking solution to pipe video round the home from a residential gateway. Again, Bluetooth is no alternative here. [6]

However, as well as supporting much higher capacities and not being mobile these technologies are a different kind of options from Bluetooth. These standards are essentially high speed but also mainly unidirectional, as they allow only very limited bandwidth used for signaling purposes towards the other direction. Bluetooth supports a much greater degree of interactivity and will be best deployed where this two-way capability is required such as voice and information retrieval applications. [6]

In general, Bluetooth is well suitable in point to point applications demanding, or highly benefiting of, wireless connectivity. Good examples of this kind of applications are mobile terminal headsets and dial-up networking between laptop and mobile terminal. Bluetooth technology suits also well in applications where there is only moderate demands for data transfer rate. Bluetooth is not the technology to fully eliminate need for cable connectivity but it definitely has some good applications and possibility to take piece of the market.

2.2 Point to multipoint applications

Although Bluetooth supports a point to multipoint topology only two profiles in the version 1.1 of the *Profiles Specification of the Bluetooth System* [9] actually implement it; Cordless telephony and LAN access. [6] Of these LAN access is by far the most widely implemented. There are also a number of issues connected to the point to multi-point topology that need to be borne in mind when designing applications.

One application of the LAN access profile is the scenario where a number of laptops (or other devices) are connected to an access point as the access point works as the master and the connected devices as slaves. More interestingly, from the ad hoc networking point of view, the profile could also be used to support a group-networking situation to network up to eight laptops with one as the master and the other seven as slaves as shown in Figure 2. The most obvious problem with this is that there is no facility for slave-to-slave communication supported by the LAN profile. Of course, there is an option that two slaves form a further piconet, thus creating a scatternet and generating the problems discussed in next chapter considering scatternets.

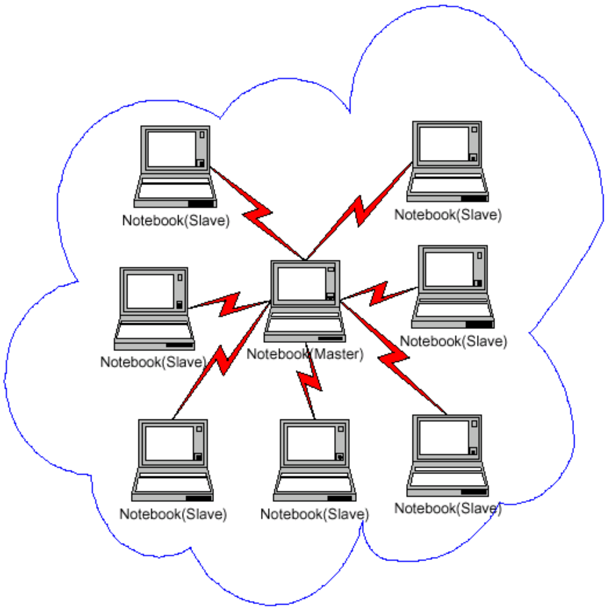

Figure 2: Single piconet ad hoc network.

The new *Bluetooth Personal Area Networking Profile* [10] is addressing this limitation in ways that will allow peer-to-peer communication and forwarding of packets between two slaves by the master working as a router. This will allow the usage of the real networking protocols such as IP. The PAN profile is still going through interoperability trials and is discussed more separately in chapter 3.

Even if we are happy with the basic piconet functionality of the master laptop supporting numerous slaves there are still a number of issues that should be noted when thinking the usability of the presented application.

Firstly there is the fact that although the slaves can come and go as they want and the application will handle these dynamics as expected, if the master leaves the piconet the whole network drops down. [6] It is clear that this is a problem in applications like used as an example here. It needs extra work from the users of the ad hoc network to decide a proper master that will be available for the whole time.

Secondly, with up to seven devices paging the master at once there are likely to be a considerable number of collisions leading to an increased network formation time. [6] Still the effect of this might not be so dramatic because the fact that often the slaves won't be joining into the network at the same time but with some time variance.

Finally, loss of bandwidth will result due to the way in which the piconet is formed. Normally a connection will have to be initiated by the slave with a master/slave switch occurring once the connection is made. This requires the master to continuously be in page scan mode, which will consume up to 10% of the available bandwidth. In the case of the fixed LAN access point this is simply part of the application it is serving, it is constantly being on the look out for new devices that may want to connect to the network. But in the group networking situation when the number of participants in the network will be known at the setup, as an example a meeting of few person, there will be no need for the master to visit page scan mode once all participants have joined. If there is no facility to switch this mode off then the application will be saddled with a significant loss of bandwidth. [6]

As conclusion of Bluetooth usage for a simple, piconet size, ad hoc networking it can be noted that there are few problems that are not currently solved and that effect to performance of Bluetooth specification to work as ad hoc networking technology. The presented problems are not however showstoppers for Bluetooth usage in simple, e.g. meeting kind of, ad hoc networking application.

In general it can still be seen that the Bluetooth technology suits well in this kind of small, piconet sized, ad hoc networks as it does not need any cable connectivity and offers moderate bandwidth for data transmission. Next we look into scatternet topology that extends Bluetooth application usage over the limit of piconet's eight simultaneously active nodes.

2.3 Scatternet applications

The concept of the scatternet is integral part of Bluetooth specification and has been under a remarkable research interest since first introduced. Anyone new to Bluetooth will be introduced to the concept of the scatternet almost immediately; the topology employed by Bluetooth is that of a master and slave forming a piconet and piconets in turn can be linked to create a scatternet covering a much wider area.

Indeed, scatternets are suggested as being preferential to a point to multipoint piconet as the AU System's *Bluetooth White paper* [16] suggests; "if a mobile user wants to connect a number of Bluetooth units to his mobile phone, the best way to get high data transmission capacity is to form as many piconets as possible in one scatternet. Every connection is using a piconet's maximum capacity (721 kbps)."

Sound good in theory, but the reality is that the scatternet functionality to date is still essentially that - just theory. Many observers claim that the scatternet functionality is not defined precisely enough in the Bluetooth specification to ensure interoperability and that that as a result many developers of Bluetooth radios are not even attempting to implement it. Furthermore none of the existing profiles support scatternet functionality. [6]

Also this situation is being remedied by the PAN Working Group, which is extending Bluetooth to provide true IP-based personal area networking capability, which will involve tightening up the scatternet specification. Making scatternets work via a profile in this way, as opposed to altering the radio or base-band specification is necessary in order to maintain the basic stability of the version 1.1 of the specification. [6]

2.3.1 Accidental scatternets

Today, if a silicon vendor has implemented scatternet functionality there are circumstances in which a user may inadvertently create a scatternet and because of the almost certain lack of interoperability that the scatternet specification involves the application will then fail - giving the user the impression Bluetooth is unreliable.

The first can occur when a slave initiates a piconet connection by paging the master which is waiting in page scan mode, which then undergoes a master/slave switch. If the master/slave switch occurs at the same time as the ACL link (see the *Core Specification of the Bluetooth System* [4]) is created this will be OK, but if the switch occurs after the creation of the ACL link and a connection to a third device is created prior to the switch a scatternet may ensue rather than a point to multipoint piconet. [6]

A second way of creating an unwanted scatternet is when multiple profiles are being run simultaneously on one device, an issue that the version 1.1 of the specification does not deal with. [6] Consider the case of a mobile phone providing simultaneous Internet access for a PDA and a voice connection to a headset. The desired topology would be a piconet in which the phone was the master and PDA and headset both slaves.

But if the PDA initiates the link to the phone it will be the master. When the headset joins in the phone needs to be the master to the headset and then initiate a master/slave switch with the PDA to create a single piconet. Failure to do so will result in an attempted scatternet with the phone a slave to the PDA and master to the headset. The master/slave switch is not mandated by the any of the profiles involved so even if the phone does try to implement it the PDA may not be in a position to accept the switch.

For the user this is of considerable concern and, given the likely popularity of such a PDA, phone and headset arrangement, one that is more than likely to be encountered. Because a scatternet could be formed with no guarantee of interoperability then the arrangement will fail in these circumstances. Even worse, this will depend on the order in which the applications are launched; sometimes a scatternet will form and not work, sometimes the desired piconet will form and the application will work.

To the user, to whom the intricacies of his situation will be irrelevant, Bluetooth will appear to work sometimes and not at others - a level of reliability that is worse than simply not working at all. The PAN Working Group is tackling the network formation issues raised by the above example as well as many research studies made in industry and universities. These studies are shortly introduced in chapter 5.

3 Personal Area Networking profile

The LAN access point profile as it is specified today enables an access point to act as a bridge between a Bluetooth device and a local area network, by running multiple PPP (Point to Point Protocol) connections, with up to seven Bluetooth devices. RFCOMM runs on top of PPP, which in turn runs on either TCP/IP or UDP/IP. [4]

This allows basic services such as file access, printing, intranet or Internet access, synchronization and more advanced services such as cordless telephony and voice over IP. Although PPP allows LAN access for multiple Bluetooth devices in a ‘star’ topology it is only allowing communication by serial cable emulation and is not a true networking protocol. It does not support any slave-to-slave communication and its prospects for scalability in terms of the number of devices that can be networked are very limited. In addition no facility for hand-off between access points, to allow seamless mobility between access points, is provided.

For this Bluetooth needs to support true networking protocols, most notably IP, which means running TCP/IP over L2CAP which in turn requires a new profile to be defined.

This is the charter of the Bluetooth PAN Working Group that has been tasked with: [10]

- Enabling IPv4, IPv6 and other common networking protocols to run over Bluetooth whilst allowing existing networking applications to work
- Supporting slave to slave communication
- Allowing both the above to work in both ad hoc mode (device to device) and infrastructure mode (in which access points are connected to the fixed infrastructure).

To achieve this the PAN WG has proposed a new protocol, Bluetooth Networking Encapsulation Protocol (BNEP), which is described as providing an Ethernet-like networking framework. It supports IPv4, IPv6, all IETF (Internet Engineering Task Force) protocols and also packet header compression to minimize transmission overheads. It is claimed that it will lead to greater ease of Bluetooth use as it will allow existing networking applications designed for these protocols to interface to Bluetooth and also supports ISO layer 2 bridging, similar to other wireless LANs and which is the foundation of access point hand-off. [6]

It will enable devices to operate in more of a peer-to-peer fashion rather than the usual master-slave topology and so help enable peer-to-peer applications such as gaming.

The profile defines three different operational roles: [10]

- Pan User (PANU) in which a device acts as a client of either of the following two cases.
- Group Network (GN) in which devices are networked together but with no access point supporting communication with a wider infrastructure.
- Network Access Point (NAP) which supports the infrastructure case and connects devices via an access point to another network.

The Pan profile promises to make Bluetooth into a true IP networking technology and, especially when acting as a NAP will provide more choice in a number of applications where the networking functionality of 802.11b has to date made it the only realistic alternative. [6]

Bluetooth Personal Area Network profile specification [10] is currently at version 0.95a and conducting interoperability trials. Bluetooth Network Encapsulation Protocol specification [11] provides the network support required for the Personal Area Network profile specification and is also at version 0.95a.

4 Service discovery

As shown already, Bluetooth specification is a part of a new generation of much more fluid networks in which devices and services are not part of the fixed infrastructure but are continually leaving and joining different networks in an ad hoc fashion. Networks have traditionally been defined simply by the connections they provide but in future the ability to connect with a network and its devices will be taken for granted. The real value will lie in finding out what the capabilities of other devices are, what services the network can provide, how a device can access these services, e.g. what protocols and drivers are required. Also promoting a device's own services to the network and possibly even billing for services is almost essential functionality. All this is called service discovery, a facility that is supported by Bluetooth via the Service Discovery Protocol (SDP).

A key aspect of service discovery is the support it provides for self-configuration of devices. In static networks configuration is not such a big issue as it is usually done once, at installation, and the details of the various available services on the network and where to find them are held in a central directory. But in dynamic networks of the sort that mobile Bluetooth devices will be part of such a solution has considerable shortcomings and cannot be used - instead the devices must be able to self-configure. In a consumer environment this ability to self-configure must also be very simple/almost invisible, widely applicable and easy to use if the technology is to reach the mainstream mass market.

Aside from Bluetooth SDP there are also various other technologies able to carry out a service discovery function in Bluetooth environment. To support these protocols, there is a Bluetooth Working Group, Extended Service Discovery Profiles Working Group (ESDP). This working group is mapping Bluetooth SDP to a variety of other service discovery protocols, thereby increasing the mutual utility of devices supporting the individual protocols. [6]

5 Performance studies

In this chapter our main interest is Bluetooth ad hoc scatternets' formation and performance aspects. There are several studies made about optimizing scatternet formations. These studies try to overcome the problem of arranging scatternets in the most efficient way for routing between nodes.

In *Performance Aspects of Bluetooth Scatternet Formation* [7] study by Miklós et al it was noted by using a statistical approach that two characteristics seem to be valid in performance of scatternet formation. First the amount of bridging overhead and secondly the number of established Bluetooth links. By bridging overhead is meant the number of nodes participating in more than one piconet i.e. working as both master and slave. Increasing the number of links first allows more traffic to be carried by the network, but this trend is later reversed due to the increased overhead of a node being a member of more and more piconets. So, there is a link number when the throughput is maximized.

Aggarwal et al. introduce in *Clustering algorithms for wireless ad hoc networks* [12] a scatternet algorithm. Their algorithm first partitions the network into independent piconets, and then elects a `super-master' that knows about all the nodes. However, the resulting network is not a scatternet, because the piconets are not inter-connected. Thus, another phase of re-organization is required with will add the time complexity of the algorithm. [8]

Also Záruba et al. have introduced a solution to arrange a scatternet with a centralized manner in *Bluetrees – Scatternet Formation to Enable Bluetooth-Based Ad Hoc Networks* [5] study. As a matter of fact, they introduce two similar protocols. The first protocol organizes the Bluetooth nodes into a rooted tree, a bluetree, in which each node participates at most two piconets, keeping bridging overhead low. The second protocol has more distributed behavior as every node is allowed to assume at most tree roles. This adds more bridging overhead but still not in critical amount.

Salonidis et al. discuss in *Proximity Awareness and Fast Connection Establishment in Bluetooth* [13] about symmetric connection between a pair of Bluetooth devices. In the introduced symmetric protocol, the devices switch states ('sender' and 'receiver') with a random schedule. The results show that the connection establishment delay between two nodes can be reduced if correct parameters are used in e.g. mean state residence time. Still, it should be noted that the paper is avery high-level study and the introduced protocol does not work well as such with several nodes trying to form scatternet.

Salonidis et al. also present a scatternet formation algorithm - BTCP (Bluetooth Topology Construction Protocol) in *Distributed Topology Construction of Bluetooth Personal Area Networks* [14] paper. Solution utilizes protocol discussed in [13]. BTCP has two phases: first, a leader is elected with a complete knowledge of all devices, and second, this leader will tell other devices how a scatternet should be formed. Since a single device determines the topology, BTCP has more flexibility in constructing the scatternet.

Performance of a New Bluetooth Scatternet Formation Protocol [8] by Law et al. also shows that there is need for an efficient protocol to form an ad hoc scatternet from isolated Bluetooth devices. The introduced algorithm produces scatternet with some desirable properties: small number of piconets for minimizing inter-piconet interference as packet collisions, and low device degrees for avoiding network bottlenecks. In addition, according to the simulations, the diameter of the scatternet, which corresponds to the maximum routing distance between nodes, is O(log n). There is also demonstrated that no single device is particularly exhausted by the protocol, as there is no centralized master arranging the whole scatternet.

Paper *Forming Scatternets from Bluetooth Personal Area Networks* [15] by Tan et al. describes TSF, Tree Scatternet Formation algorithm. TSF also connects nodes in a tree structure that simplifies packet routing and scheduling. Unlike earlier protocols introduced, the design does not require that all devices be within radio range of each other, nor does it restrict the number of nodes in the network. It also allows nodes to arrive and leave at arbitrary times, incrementally building the topology and healing partitions when they occur.

6 Conclusions

In this paper we discussed about different aspects of Bluetooth technology suitability for ad hoc networking. As result is was shown that there are several issues limiting the functionality of Bluetooth technology in ad hoc environment.

Most of these issues are connected to loose specification of scatternet formation. As result there are several research papers published proposing different scatternet formation protocols to correct this issue. Evaluation of these papers show that there is some good propositions available to address this issue efficiently. Still there is no widely utilized scatternet formation protocol implemented in current Bluetooth devices that would enable uniform, and efficient, ad hoc scatternet formation.

Also the pending *Bluetooth Personal Area Networking Profile* [10] is hoped to address in many expectations to correct issues concerning Bluetooth ad hoc networking functionality. The PAN profile is extending Bluetooth to provide true IP-based personal area networking capability by allowing peer-to-peer communication and forwarding of packets between two slaves by the master working as a router. The PAN profile is the first Bluetooth profile fully supporting scatternet topology.

As final conclusion it seems that today Bluetooth is not yet a commercial solution for seamlessly providing ad hoc networking capability to portable devices such as laptops and PDA's. However, the first commercial product implementations of the new PAN profile will soon show if Bluetooth is up to this task as being able to utilize it's scatternets efficiently to form ad hoc networks. The possibilities are there, we just have to wait and see markets response.

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