ENERGY-EFFICIENT BLUETOOTH SCATTERNET FORMATION BASED ON DEVICE AND LINK CHARACTERISTICS

A THESIS
SUBMITTED TO THE DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING
AND THE INSTITUTE OF ENGINEERING AND SCIENCE
OF BILKENT UNIVERSITY
IN PARTIAL FULLFILMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

By
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August 2003

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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August 2003

Bluetooth is a promising ad hoc networking technology. Although construction and operation of piconets are well defined in Bluetooth specifications, there is no unique standard for scatternet formation and operation.

In this thesis, we propose a distributed and energy-efficient Bluetooth ***S***catternet ***F***ormation algorithm based on ***Devi***ce and ***L***ink characteristics (SF-DeviL) that is compatible with Bluetooth specifications. SF-DeviL handles energy efficiency using classes of devices, battery levels and the received signal strengths. SF-DeviL forms scatternets with tree topologies that are robust to battery depletions, where devices are arranged in an hierarchical order in terms of battery power and traffic generation rate. SF-DeviL is dynamic in the sense that the topology is reconfigured when battery levels are depleted, thereby increasing the lifetime of the scatternet. Unlike many of the algorithms in the literature SF-DeviL is also multihop, i.e., there is no requirement for each node to be in the transmission range of all other nodes.

Keywords: Bluetooth, scatternet formation, energy efficiency, class of device, received signal strength, RSSI, battery level, multihop, tree topology, distributed.

ÖZET

ENERJİ-VERİMLİ
AYGIT VE BAĞ ÖZELLİKLERİNE DAYALI
BLUETOOTH MULTİPİKONET FORMASYONU

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Bluetooth, kısa mesafelerde gelecek vadeden bir tasarsız ağ teknolojisi olduğundan, son yıllarda popülerlik kazanmıştır. Bluetooth pikonetlerinin oluşum ve işleyişi Bluetooth spesifikasyonlarında belirlenmiş olmasına rağmen, multipikonet formasyon ve işleyişinin henüz bir standardı yoktur.

Çalışmamızda, aygıt ve bağ özelliklerini kullanarak multipikonet oluşumunu sağlayan bir algoritma geliştirdik. SF-DeviL (***S***catternet ***F***ormation algorithm based on ***Devi***ce and ***L***ink characteristics) algoritması, aygıt sınıfı, pil seviyesi ve alınan sinyal gücü bilgilerini kullanarak, düğümlerin enerji verimliliğini arttırıyor. SF-DeviL, aygıtların pil güçlerine ve trafik üretim oranlarına dayalı hiyerarşik bir ağaç topolojisi oluşturarak, pil tükenmelerine karşı dayanıklı multipikonetler oluşturuyor. SF-DeviL, multipikonet iletişimi boyunca, azalan pil seviyeleriyle tekrar çalıştırılarak multipikonet ömrünü uzatan dinamik bir yapıya sahiptir. SF-DeviL ile her aygıtın diğer bütün aygıtların iletim eriminde olma zorunluluğu yoktur, kısacası multisekmedir.

Anahtar Kelimeler: Bluetooth, multipikonet formasyonu, enerji verimliliği, aygıt sınıfı, alınan sinyal gücü, RSSI, pil seviyesi, multisekme, ağaç topolojisi, dağıtık.

ACKNOWLEDGEMENTS

I would like to express my gratitude to my supervisor Assist. Prof. Dr. Ezhan Karaşan for his instructive comments in the supervision of the thesis.

I would like to express my special thanks and gratitude to Assist. Prof. Nail Akar, Prof. Hayrettin Köymen for evaluating my thesis.

I would like to express my thanks to my family and Özgü for their endless love and support throughout my life.

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Chapter 1

INTRODUCTION

The widespread usage of information intensive consumer devices has come up with a new networking paradigm for interconnecting them. Mobility of these devices and variety of applications have led to a wireless networking solution where the network is formed in an ad hoc manner, without the need for manual configuration and wired structure. A computer connected to a keyboard, a mouse, a pair of loudspeakers, a PDA in a personal area network or a laptop connected to a coffeemaker, a security system, a house appliance are possible situations where a wireless short-range networking solution is useful.

Bluetooth is a new and promising technology, standardized in 1999, that enables devices to form short-range wireless ad hoc networks. Its technical features such as non-line-of-sight communication, low power consumption, low cost and usage of frequency hopping physical layer are some of the features that provide advantages for Bluetooth over other competing technologies.

By today's Bluetooth technology, Bluetooth enabled devices are capable of forming a network of maximum 8 active devices which is called a *piconet*. In a piconet a node has the master role and the rest have slave roles. But Bluetooth technology promises much more beyond connectivity between a small number of devices in an isolated piconet. Bluetooth can be extended to interconnect multiple piconets to form a larger ad hoc network, which is called a *scatternet*, consisting of hundreds of devices. Also, multihop scatternets can provide connectivity over distances greater than the short radio range. The frequency hopping technique employed by Bluetooth enables multiple piconets to communicate at the same time and at the same place with little interference between them.

Although piconet formation and operation are well defined in Bluetooth specifications, there is no standard for scatternet formation and operation [1]. The Bluetooth specification enables the formation of a larger network from many nodes but it does not define an exact method for scatternet formation. The problem of scatternet formation can be stated to be the assignment of master, slave and bridge roles to Bluetooth nodes.

Scatternet formation is a new research problem, the studies of which gained acceleration in the last few years. Research related to Bluetooth scatternet formation can be separated into two groups: methods for scatternet formation and scatternet topology optimization.

What makes Bluetooth scatternet formation a challenge is the differences of Bluetooth networks and other networks. Bluetooth networks are highly dynamic, small (about tens of nodes), ad hoc, where devices have low computational and battery resources. Also due to frequency hopping channel, each link must be built up before communication.

The published methods for Bluetooth scatternet formation show differences in their approaches. First studies tried to form scatternets by centralized approaches and formed onehop scatternets [2][3], which later turned out to be impractical and left their place to distributed multihop scatternet formation methods.

Published methods also differ in the resulting scatternet topology: tree [4-6], star[7] and mesh topologies[8-10] are tried. In [11], an analysis of Bluetooth scatternet topologies is made, and the results show that the optimum topology is application dependent.

Bluetooth scatternet formation algorithms suitable for dynamic environments are partially addressed in [4] and [6], where group arrivals are handled by the scatternet formation method.

None of the above scatternet formation methods considers energy efficiency that is especially important in the operation and lifetime of the formed scatternet. Energy efficient techniques in routing protocols for Bluetooth scatternets have been investigated, and it is shown that a considerable gain in network life can be achieved by using distance based power control and battery level based master-slave switch [12]. But such techniques are not considered for formation or operation of scatternets.

In this thesis, we propose a new scatternet formation algorithm named as SF-DeviL (***S***catternet ***F***ormation based on ***Devi***ce and ***L***ink Characteristics). SF-DeviL runs in a distributed fashion and forms energy efficient, multihop scatternets. SF-DeviL is appropriate to handle dynamic environments.

The primary goal of SF-DeviL is to form a scatternet where energy management can be done efficiently throughout the formation and lifetime of the network. SF-DeviL handles energy efficiency by using: 1) classes of devices, 2) the received signal strengths and 3) battery levels of devices. SF-DeviL uses class of device information, e.g., it assigns roles to nodes by looking whether it is a laptop, a PDA, a sensor etc. None of the published scatternet formation methods consider the class of device information, which can expose many features of a node such as mobility, traffic generation rate and battery capacity. By SF-DeviL, each node measures received signal strength for each link and quantizes it to give priority to shorter links. Using power control at these shorter links results in less power requirement for the transmission of a packet and reduces interference to other systems using the same frequency band. SF-DeviL also keeps track of battery levels throughout scatternet communication and rearranges the scatternet where it pushes low battery level devices toward the leaf nodes of the tree, in order to increase lifetime of each device and the lifetime of the scatternet. As a result, SF-DeviL forms scatternets that are robust to mobility and battery depletions.

Chapter 2 is a brief overview of Bluetooth technology to constitute a background. Chapter 3 is a discussion on open problems regarding scatternets, challenges and solutions to the scatternet formation problem, an overview of published scatternet formation solutions. In Chapter 4, SF-DeviL is explained in detail and its features are discussed. Chapter 5 includes performance evaluation of SF-DeviL that is done through simulations and simulation results are clarified. The thesis concludes with Chapter 6 where a summary of the study and future work is given.

Chapter 2

OVERVIEW OF BLUETOOTH TECHNOLOGY

The Bluetooth wireless technology operates in the unlicensed 2.4-2.5 GHz Industrial, Scientific, Medicine (ISM) frequency band. Bluetooth radio employs a fast (1600slots/sec) frequency hopping spread spectrum (FHSS) technique that gives robustness against interference and fading. The radio hops in a pseudo-random fashion on 79 one-MHz channels. A slotted channel is applied with a nominal slot length of 625 μs. For full duplex transmission, a Time-Division Duplex (TDD) scheme is used. On the channel, information is exchanged through packets. Each packet is transmitted on a different hop frequency. A packet nominally covers a single slot, but can be extended to cover up to three or five slots.

The modulation technique is binary Gaussian frequency shift keying (GFSK), and the band rate is 1Msymbol/sec. The bit time is 1msec, and the raw transmission speed is 1Mb/sec.

Bluetooth supports both voice and data communication using 2 types of physical links: Asynchronous Connectionless (ACL) and Synchronous Connection-Oriented (SCO). SCO is a symmetric, point-to-point link between a master and a specific slave. The master will send SCO packets at regular intervals. Thus, an SCO link can be considered to be a circuit-switched connection. SCO links support time-delay sensitive traffic such as voice. An ACL link provides a packet-switched communications between a master and a slave. Briefly, Bluetooth uses a combination of circuit and packet switching. Each voice channel supports a 64 kb/s synchronous (voice) channel in each direction. The asynchronous channel can support maximal 723.2 kb/s asymmetric (and still up to 57.6 kb/s in the return direction), or 433.9 kb/s symmetric.

Bluetooth has low power consumption. Bluetooth specification allows for three different types of radio transmit powers:

- Class 1 = 100mW (20dBm)
- Class 2 = 2.5mW (4dBm)
- Class 3 = 1mW (0dBm)

These power classes allow Bluetooth devices to connect at different ranges. The maximum range for a Class 1 is 100m, whereas it is 10m for Class 3. Since Bluetooth applications are mostly short-range today, owing to the importance of low energy consumption for mobile devices, Class 2 and 3 are used mostly.

One of the features of Bluetooth that accelerates its penetration into the market is its low cost which is aimed to be taken down to $5 (currently $10).

2.1 Topology

The smallest operation unit of Bluetooth is a piconet. A piconet consists of a master and up to seven active slave nodes as shown in Figure 2.1. Any device can become a master or a slave. These roles are only logical states.

The master regulates and controls the traffic by polling the slaves in a Deficit Round Robin fashion. A slave is only allowed to transmit upon receiving from the master as shown in Figure 2.2. During a time slot one Bluetooth device may transmit. The master starts its transmission in even-numbered time slots only, and the slave starts its transmission in odd-numbered time slots only.

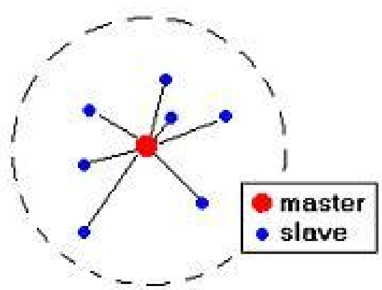


Figure 2.1: Topology of a piconet

Slaves of a piconet are synchronized to the master's frequency hop sequence, which is particular to each piconet. Slaves calculate this particular hop sequence using the master's Bluetooth device address (BD_ADDR) and clock information that are exchanged during master-slave connection establishment procedure. To identify each slave, the master assigns a locally unique active member address (AM_ADDR) to the slaves participating in active communications in the piconet.

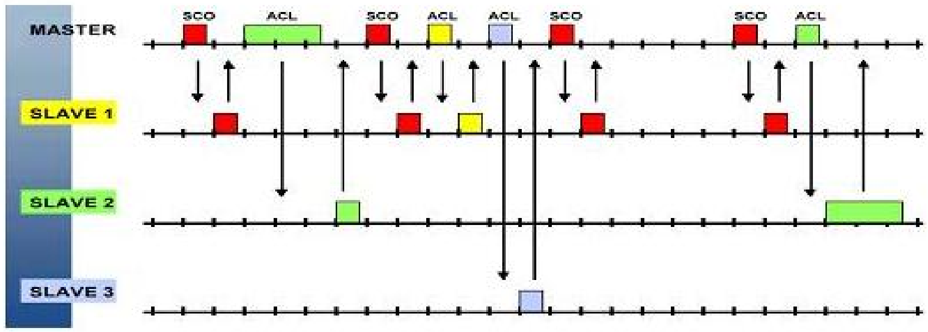


Figure 2.2: Communication in Bluetooth provided by master polling slaves

Piconets can co-exist in time and space since each piconet uses a different frequency hop sequence. The network formed by connecting several piconets via shared nodes is called a *scatternet,* and the shared nodes are called *bridge*s. Bridge nodes may be master in one piconet and slave in the other (M/S), or slave in several piconets (S/S, S/S/S...etc.) or master in one piconet and slave in the others (M/S/S) as illustrated in Figure 2.3. Bridge node cannot be master in more than one piconet since the master's frequency hop sequence should be particular to a single piconet. Bridge nodes participate in different piconets on a time-division multiplex basis.

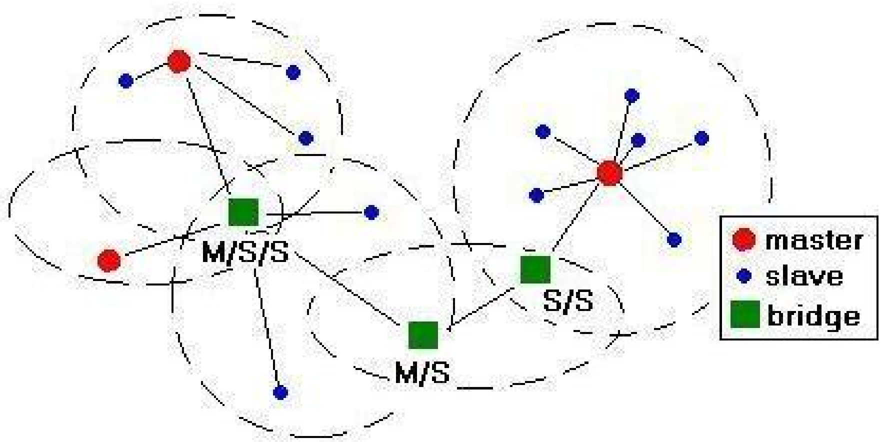


Figure 2.3: Topology of a scatternet where bridge nodes have undertaken M/S, S/S and M/S/S roles

2.2 Bluetooth Device Address

Bluetooth device address (BD_ADDR) uniquely identifies each Bluetooth device and it is 48 bits long. The format of the BD_ADDR is as shown in Figure 2.4.

Non-significant address part	Upper Address Part (UAP)	Lower Address Part (LAP)
16	8	24
LSB		MSB

Figure 2.4: Structure of BD_ADDR

BD_ADDR is used for calculating various access codes, described in detail below. Frequency hopping sequences are calculated from these access codes. Thus, to know a hopping sequence of a device one needs to know the device's BD_ADDR.

2.3 Packets

The packets used on the piconet are related to the physical links they are used in. For each of the SCO link and the ACL link, 12 different packet types can be defined. Four common packet types that are used during connection establishment procedure are ID, NULL, POLL and FHS packets, which are listed in Table 2.1. A general format of a Bluetooth packet is shown in Figure 2.5.

Access Code	Header	Payload
72	54	0-2745
LSB		MSB

Figure 2.5: General format of a Bluetooth packet

ID	- consists of the DAC or IAC - has a fixed size of 68 bits - used in paging, inquiry and response routines
NULL	- consists of a CAC and packet header only - has fixed length of 126 bits - used to return link information to the source regarding the success of previous transmission or status of RX buffer
POLL	- similar to null packet, but it does have to be acknowledged
FHS	- a special type of a control packet revealing the BD_ADDR and clock of the sender - exchanged during connection establishment

Table 2.1: A brief summary of control packets used for connection establishment

2.3.1 Access Code

Access code is derived from lower address part (LAP) of BD_ADDR. Access code is a field of a Bluetooth packet. There are 3 types of access codes: Channel Access Code (CAC), Device Access Code (DAC), and Inquiry Access Code (IAC). IAC can be general (GIAC) or dedicated (DIAC).

A Bluetooth unit that tries to discover devices in range sends packets with GIAC since no prior knowledge of BD_ADDR of the neighboring device exists. After getting the BD_ADDR of the neighboring device, it sends packets with DAC to be received by that specific device.

Inside a piconet, packets with a specific CAC to that piconet are exchanged so that any other packet belonging to another piconet, i.e. with a different CAC is not accepted.

Channel Access Code (CAC):	- The channel access code identifies a piconet. This code is included in all packets exchanged on the piconet channel. - Derived from master's BD_ADDR.
Device Access Code (DAC):	- This code is included in a packet sent to a specific device. It is used used during page and page scan substates of the connection establishment procedure. - Derived from paged unit's BD_ADDR.
Inquiry Access Code (IAC):	- This code is included in a packet sent to any device for discovery purposes. It is used during inquiry and inquiry scan substates. - There is one general IAC (GIAC) and 63 dedicated IACs (DIAC) used to inquire for specific classes of devices.

Table 2.2: A brief summary of access codes

2.3.2 FHS Packet

The FHS packet is a special control packet revealing, among other things, the Bluetooth device address and the clock of the sender. The payload contains 144 information bits plus a 16-bit CRC code. The payload is coded with a rate 2/3 FEC bringing the gross payload length to 240 bits. The FHS packet covers a single time slot.

The structure of the payload of the FHS packet is as shown in Figure 2.6, where brief explanations of fields are listed in Table 2.3.

Parity bits	**LAP**	**Un-defined**	**SR**	**SP**	**UAP**	**NAP**	**Class of Device**	**AM_ ADDR**	**CLK**	**Page scan mode**
34	24	2	2	2	8	16	24	3	26	3

LSB **MSB**

Figure 2.6: FHS payload structure

NAP-UAP-LAP	BD_ADDR of the unit that sends the FHS.
Parity bits	Form the first part of the sync word of the access code of the unit that sends the FHS.
SR	Scan Repetition field, indicates the interval between two consecutive page scan windows.
SP	Scan period, indicates the period in which the mandatory page scan mode is applied after transmission of an inquiry response message.
CLK	Contains the value of the native system clock of the unit that sends the FHS packet, sampled at the beginning of the transmission of the access code of this FHS. This clock value has a resolution of 1.25ms.
Page Scan Mode	Indicates which scan mode is used by default by the sender of the FHS.

Table 2.3: Description of the FHS payload

The FHS packet plays an important role in Bluetooth connection establishment. For communication to take place between two Bluetooth devices, their frequency hop sequences have to be the same. As mentioned previously, frequency hop sequence of a piconet is calculated using the master’s access code and clock information. Thus, a slave candidate has to get this information which is exchanged inside frequency hop synchronization (FHS) packet. Briefly, for two devices to connect, the device that will undertake slave role has to get FHS packet from the master.

2.3.2.1 Class of Device/Service Field of FHS Packet [13]

The class of the device where the Bluetooth module is embedded is known by the Bluetooth module. Furthermore, this knowledge is exchanged between two devices establishing a link. The device class information together with service information is exchanged by the 24 bit long Class of Device/Service (CoD) field of the FHS packet as shown in Figure 2.6.

The Class of Device/Service (CoD) field has a variable format. The format is indicated using the 'Format Type field' within the CoD. In the “format #1” of the CoD, i.e. “Format Type field = 00”, 11 bits are assigned for device classes and 11 for service classes as shown in Figure 2.7.

Format type	**Major Device Address**	**Minor Device Address**	**Service Classes**
2	6	5	11

LSB **MSB**

Figure 2.7: Structure of the Class of Device/Service field (first format type)

Service classes are primarily of a “public service” nature. Currently 9 service classes are defined: Limited discoverable mode, positioning, networking (LAN, Ad hoc, ...), rendering (printing, speaker,...), capturing (scanner, microphone,...), object transfer, audio, telephony, information (WEB-server, WAP-server,...). 2 bits of Service Classes Field are reserved for future use.

The remaining 11 bits of CoD field are divided into two subcategories: major and minor device classes and are used to indicate device type category and other device-specific characteristics.

2.3.2.1.1 Major Device Class

The Major Class segment is the highest level of granularity for defining a Bluetooth Device. The main function of a device is used to determine the major class grouping. There are 32 different possible major classes. The assignment of this Major Class field is given in Table 2.4.

12	11	10	9	8	Major Device Class
0	0	0	0	0	Miscellaneous*
0	0	0	0	1	Computer (desktop, notebook, PDA, organizers, ...)
0	0	0	1	0	Phone (cellular, cordless, payphone, modem, ...)
0	0	0	1	1	LAN /Network Access point
0	0	1	0	0	Audio/Video (headset, speaker, stereo, video display,...)
0	0	1	0	1	Peripheral (mouse, joystick, keyboards, ...)
0	0	1	1	0	Imaging (printing, scanner, camera, display, ...)
1	1	1	1	1	Uncategorized, specific device code not specified**
X	X	X	X	X	All other values reserved

Table 2.4: Major Device Classes

2.3.2.1.2 Minor Device Class

The 'Minor Device Class field' (bits 2 to 7 in the CoD), are to be interpreted only in the context of the Major Device Class (but independent of the Service Class field). Thus the meaning of the bits may change, depending on the value of the 'Major Device Class field'. For example, by setting the major class field as ‘computer’, different settings of the minor device class field end up with desktop, server-class computer, laptop, handheld PC/PDA or wearable computer device classes.

Many of the minor device class field bits are reserved for future use, the number of which depends on the major device class. 3 bits for computer, phone and LAN/Network access point major classes; 2 bits for imaging major class and 1 bit for audio/video major class are reserved.

* Used where a more specific Major Device Class code is not suited.

** Devices that do not have a major class code assigned can use the all-1 code until classified.

2.4 Bluetooth States and State Diagram

At any time, a Bluetooth device is in one of a number of different states. There are two major states: *standby* and *connection*; in addition, there are substates, *inquiry*, *inquiry scan*, *page*, *page scan*, *inquiry response, master response and slave response* which are interim states that are used to add new slaves to a piconet. A simplified state diagram is given in Figure 2.8.

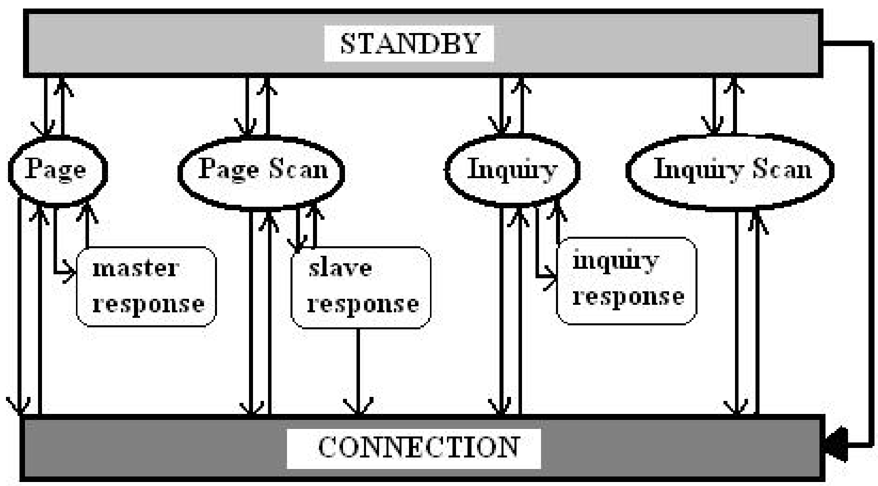


Figure 2.8: Bluetooth Device State Diagram

2.4.1 Standby

Standby state is the default state of the Bluetooth device. In it the device uses a low power mode.

2.4.2 Inquiry (I)

A unit that wishes *to discover* other Bluetooth units in range enters *inquiry* substate. It continuously transmits inquiry messages at different hop frequencies. Between inquiry transmissions the unit listens for responses (which is an FHS packet). It transmits two inquiry messages in each TX slot and listens for a response in the preceding RX slot as shown in Figure 2.9.

If the response is received, it is not acknowledged and the probing unit continues with the inquiry transmissions. The unit leaves inquiry state either when it received a predetermined number of responses or when the InquiryTO timer runs out.

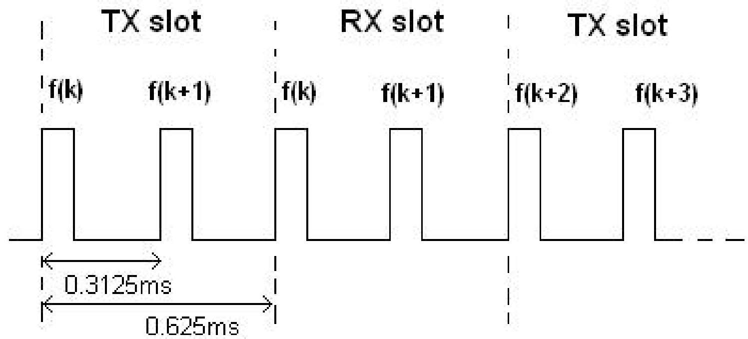


Figure 2.9: RX/TX cycle of Bluetooth transceiver in Inquiry mode

The inquiry message broadcast by the source does not contain any information about the source. However, it may indicate which class of devices should respond. There is one general inquiry access code (GIAC) to inquire for any Bluetooth device, and a number of dedicated inquiry access codes (DIAC) that only inquire for a certain type of devices.

During an inquiry substate, the discovering unit collects the Bluetooth device addresses and clocks of all units that respond to the inquiry message. It can then, if desired, make a connection to any one of them by means of the previously described page procedure.

A hopping sequence consists of two groups of frequencies: train A and train B (each of which are 16 frequencies long). According to the Bluetooth standard [1] a single train must be repeated Ninquiry =256 times before another train is used. At least three train switches are needed (4 train sequences). Since each train is 10ms long, the inquiry procedure can take up to 10.24s.

It is not specified how often a unit should leave standby or connection to perform inquiry. It might be periodic or upon user request. These choices are left up to the implementers.

2.4.3 Inquiry Scan (IS)

A unit that wishes to be discovered by other Bluetooth in range enters *inquiry scan* substate. It continuously listens for inquiry messages at different hop frequencies.

The period of inquiry scan can be 0s (continuous scan) – R0, 1.28s – R1 mode, or 2.56s – R2 mode. A scanning unit listens for an IAC for *Tw_inquiry_scan* seconds. Tw_inquiry_scan should be long enough to scan 16 frequencies (1 train). Because one train lasts for 10ms, Tw_inquiry_scan should also be 10ms. During these 10ms the receiver of the scanning device listens on a single frequency determined by the inquiry scan hopping sequence and the current value of the device's clock. The scanning device changes its listening frequency according to inquiry hopping sequence every 1.28s.

2.4.4 Page Scan (PS)

Page scan works similar to inquiry scan, however, in page scan a unit listens for its own unique DAC and it alone can respond. There are 32 paging frequencies, which comprise a page hopping sequence, determined by the paged unit's BD_ADDR. Every 1.28s, a different listening frequency is selected as in inquiry scan. During a scan window the unit listens on one frequency.

2.4.5 Page (P)

When a Bluetooth unit wants to make a connection to another unit, it pages that unit. *Paging* means sending an ID packet with a certain DAC in it over and over again until a response is received. The master does not know exactly when the slave wakes up and on which hop frequency, therefore it transmits a train of identical DACs at different hop frequencies and listens in between for responses.

The master uses the slave's BD_ADDR and an estimate of the slave's clock to determine the page hopping sequence. To compensate for the uncertainty in the knowledge of a slave's clock, the master will send its page message during a short time interval on a number of wake-up frequencies. During each transmission slot the master sequentially transmits on 2 different hopping frequencies. The page hopping sequence of 32 frequencies is divided into two trains of 16 frequencies each and each train is repeated for Npage times or until a response is received. Paging ends until a response is received or timeout value PageTO is exceeded.

2.4.6 Connection

In the connection state, the connection has been established and packets can be sent back and forth. In both units, the channel (master) access code and the master Bluetooth clock are used. The master starts its transmission in even slots, the slave starts its transmission in odd slots.

The connection state starts with a POLL packet sent by the master to verify the switch to the master's timing and channel frequency hopping. The slave can respond with any type of packet. If the slave does not receive the POLL packet or the master does not receive the response packet for *newconnectionTO* number of slots, both devices will return to P/PS substates.

The Bluetooth units can be in several modes of operation during the connection state: active mode, sniff mode, hold mode, and park mode.

2.5 Connection Establishment

Link formation or connection establishment in Bluetooth is a complicated and a long lasting (2,5msec - 681,875msec) procedure that has two phases. The first phase called inquiry is unique to Bluetooth and is instrumental in making a connection possible. This procedure is necessary because Bluetooth units do not know anything about each other prior to connection establishment, including each other's addresses and frequency hop sequences. This fact makes connection establishment a challenge. The second procedure is called paging, which has its analogs in other technologies. Figure 2.10 shows how a link is established in Bluetooth.

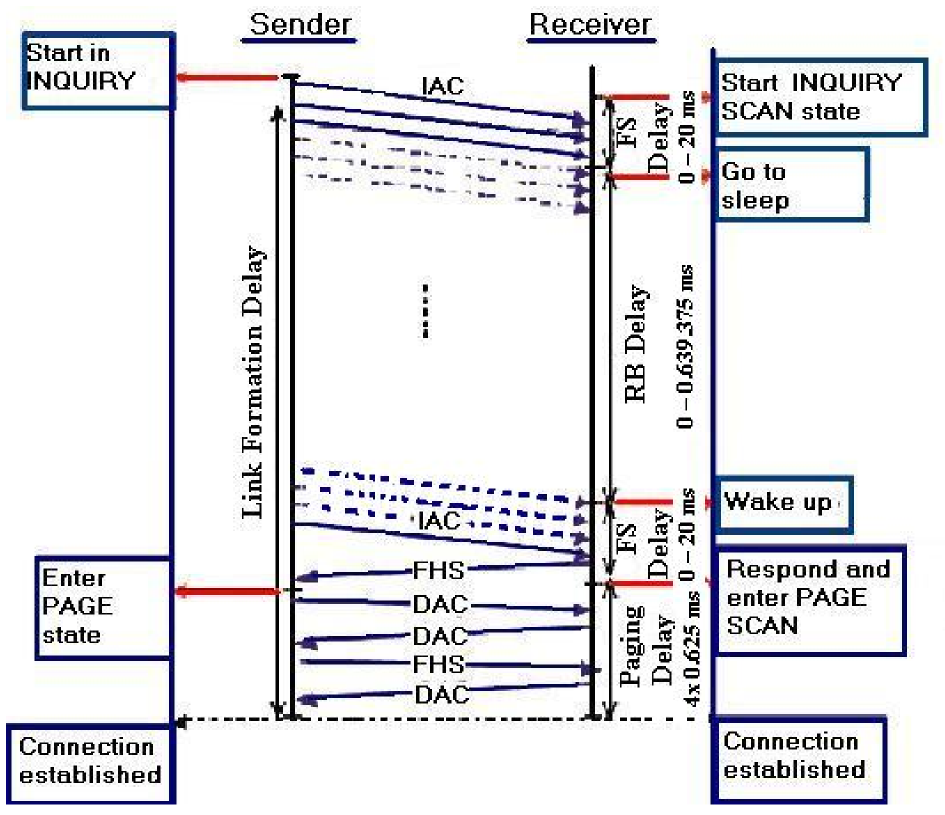


Figure 2.10: Bluetooth link formation

2.5.1 Inquiry and Inquiry Scan Procedures

A Bluetooth unit either enters inquiry state to discover other devices or inquiry scan state to be discovered by other devices in range. Every Bluetooth unit knows the GIAC, thus every unit can calculate the inquiry hopping sequence to perform inquiry. Thus, the inquirer, sends ID packets with GIAC as explained in detail in section 2.4.2.

The inquiry scanning unit, upon receiving an inquiry message, enters inquiry response substate and should respond with a FHS packet which contains the recipient's address and clock information. But, because several units might respond to an inquiry at the same time, a protocol for slave inquiry response in order to avoid or minimize the probability of collisions is needed. Thus, when the inquiry scanning unit receives an inquiry message it generates a random number, RAND, uniformly selected between 0 and 1023, returns to Connection or Standby state for duration of RAND slots. After this random backoff time, it returns to the inquiry response substate and on the first inquiry message received it will answer with an FHS packet. After sending the FHS packet, the inquiry scanning unit enters PS substate and waits to be paged for a certain time.

The inquirer unit knows the BD_ADDR and clock of the inquiry scanning unit after getting the FHS packet and can derive the frequency hopping sequence and DAC of the inquiry scanning unit. Thus, the inquirer can now page the inquiry scanning and enters page substate.

For two devices to be able to start link establishment procedure, one has to be in the inquiry and the other in the inquiry scan state. Since these substates are not assigned centrally, devices have to alternate between sender and receiver modes until they connect. In [2], it is shown that the alternation should be random. Connection is established when opposite modes coincide for long enough as illustrated in Figure 2.11.

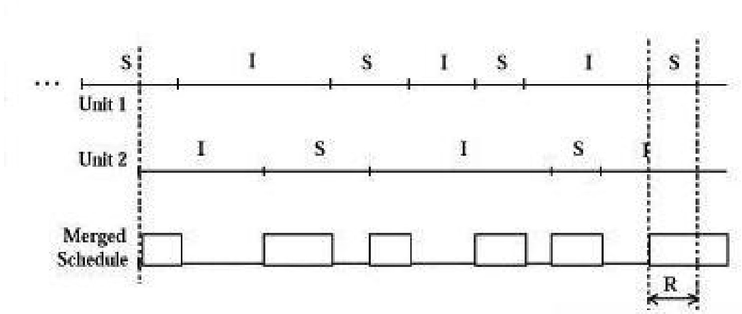


Figure 2.11: Nodes alternate between inquiry (I) and inquiry scan (S) substates until they connect

2.5.2 Page and Page Scan Procedures

The sender, having entered page substate upon receiving the FHS packet, pages the page scanning unit at the frequency that it is listening to. The page scanning unit answers with an ID packet containing DAC. The pager responds by sending the FHS packet. The page scanning unit uses the FHS information to determine the channel hopping sequence and the phase of the pager and becomes the slave of the point to point connection. It then acknowledges the FHS packet with another DAC packet. As soon as the acknowledgment is received, “the paging unit becomes the master of the connection” and may start exchanging data with the synchronized slave.

2.5.3 Master/Slave Role Switching

Bluetooth supports role switching between master and slave nodes, which means that slave becomes the master and master becomes the slave.

There are several occasions when a master-slave (MS) switch is desirable. Firstly, a MS switch is necessary when a unit paging the master of an existing piconet wants to join this piconet, since, by definition, the paging unit initially is master of a "small" piconet only involving the pager (master) and the paged (slave) unit.

Secondly, MS switch is done when a slave in an existing piconet wants to set up a new piconet, involving itself as master and the current piconet master as slave. The latter case implies a double role of the original piconet master; it becomes a slave in the new piconet while still maintaining the original piconet as master.

Thirdly, a much more complicated example is when a slave wants to fully take over an existing piconet, i.e., the switch also involves transfer of other slaves of the existing piconet to the new piconet. Clearly, this can be achieved by letting the new master setup a completely new piconet through the conventional paging scheme. However, that would require individual paging of the old slaves, and, thus, take unnecessarily long time. Instead, letting the new master utilize timing knowledge of the old master is more efficient. As a consequence of the MS switch, the slaves in the piconet have to be transferred to the new piconet, changing their timing and their hopping scheme.

By MS switch, exchange of FHS packets is done. BD_ADDRs, clock information and AM_ADDRs are exchanged through these FHS packets. The new slave gets the AM_ADDR of the older slave. Moreover, since the piconet parameters are derived from the device address and clock of the master, an MS switch inherently involves a redefinition of the piconet as well: a piconet switch. The new piconet's parameters are derived from the former slave's device address and clock. Finally, for the master and slave involved in the role switch, the MS switch results in a reversal of their TX and RX timing: a TDD switch. A detailed description of how an MS switch is done is present in [1].

2.6 Power Control

A Bluetooth transceiver has a Receiver Signal Strength Indicator (RSSI). RSSI makes power control possible. It measures the strength of the received signal and determines if the transmitter on the other side of the link should increase or decrease its output power level. The transmitter, on the other side decreases/increases the power with steps, where the step size can be selected between the maximum of 8 dB and the minimum of 2 dB.

Power control is required for power class 1 devices whereas it is optional for class 2 and 3. The power control is used for limiting the transmitted power over 0 dBm. Power control capability under 0 dBm is optional and could be used for optimizing the power consumption and overall interference level. A class 1 equipment with a maximum transmit power of +20 dBm must be able to control its transmit power down to 4 dBm or less, whereas a class 2 or 3 equipment is able to decrease its transmit power to a lower power limit of -30dBm or less as seen in Table 2.5.

The RSSI measurement compares the received signal power with two threshold levels as shown in Figure 2.12. The lower threshold level corresponds to a received power between -56 dBm and 6 dB above the actual sensitivity of the receiver. The actual sensitivity level of Bluetooth receivers should be –70dBm or better. Thus the lower threshold should be between –56dBm and about –64dBm. The upper threshold level is 20 dB above the lower threshold level to an accuracy of +/- 6 dB.

Power Class	Maximum Output Power (Pmax)	Minimum Output Power (Pmin)*	Power Control
1	100mW (20dBm)	1mW (0dBm)	Pmin<+4 dBm to Pmax *Optional:* Pmin** to Pmax
2	2,5mW (4dBm)	0,25mW (-6dBm)	*Optional:* Pmin** to Pmax
3	1mW (0dBm)	N/A	*Optional:* Pmin** to Pmax

Table 2.5: Power classes and range of power control

* Minimum output power at maximum power setting.
** The lower power limit Pmin < -30dBm is suggested but is not mandatory, and may be chosen according to application needs.

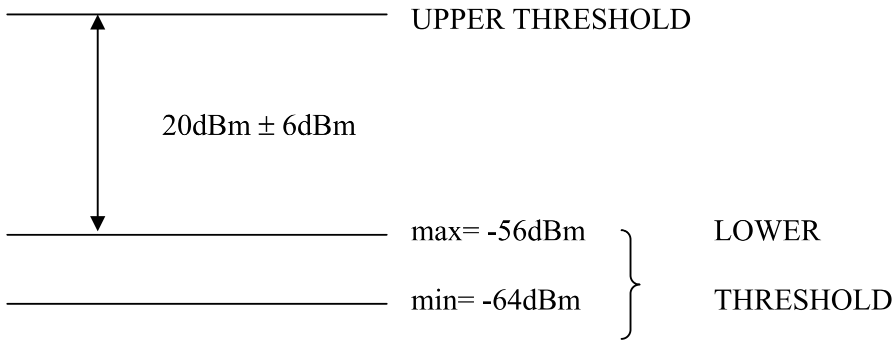


Figure 2.12: RSSI dynamic range and accuracy

Chapter 3

SCATTERNET FORMATION PROBLEM

Bluetooth technology was originally optimized for establishing point-to-point connection between devices. Today Bluetooth is seen as a promising technology for ad hoc networking and promises much more beyond connectivity between a small number of devices in an isolated piconet. Bluetooth can be extended to interconnect multiple piconets to form a scatternet, consisting of large number of devices. Also, *multihop* scatternets, where each device is not required to be in communication range of all other devices, can provide connectivity over distances greater than the short radio range. The frequency hopping technique employed by Bluetooth enables multiple piconets to communicate at the same time and at the same place with little interference between them.

The networking point of view for Bluetooth requires to solve new problems. These problems can be stated as:

I. Scatternet formation

II. Scheduling of bridge nodes

III. Routing in Bluetooth scatternets

In this thesis, the scatternet formation problem is investigated. This chapter includes an investigation of the problem and literature survey of the scatternet formation algorithms.

3.1 Scatternet Topology Formation

The Bluetooth specification enables the formation of a larger network from many nodes but it does not define an exact method for scatternet formation. The problem of scatternet formation can be stated to be the assignment of master, slave and bridge roles to Bluetooth nodes. Before considering the primary problems and solutions about scatternet formation, an evaluation of differences between Bluetooth networks and other networks should be done.

The differences between Bluetooth networks and other networks are emphasized as follows [14]:

I. *Spontaneous network:* This means the Bluetooth networks are ad hoc networks where they forward the packets of each other and they do not need an infrastructure to form a network. Also the nodes must maintain the membership information.

II. *Isolation:* The Bluetooth nodes cannot rely on infrastructure based services such as Domain Name Service (DNS) [15]. They must operate with distributed methods.

III. *Simple devices:* The devices are intended to be cheap. They have low computational and battery resources. This means that every approach must take the power save as a strong requirement into account.

IV. *Small multihop*[*] *networks:* The Bluetooth networks should be small networks. There should not be more members than about some hundred nodes. The packet forwarding is done by the nodes themselves.

V. *Connection-oriented technology:* Each link used for communication must be built up before. The cost of the active link is relatively high from the power resources point of view. A solution should make an effort on reducing the number of active links needed.

3.1.1 Problems and Solutions

Due to the above differences, primary problems with scatternet formation and solutions can be summarized as follows:

I. *Mobility:* The spontaneous network property of Bluetooth mentioned in [14] emerges from the mobile nature of devices. Since devices are mobile, topology changes may take place frequently in a scatternet, such as node additions and deletions (failure: break out, battery depletion etc.).

SOLUTION: The scatternet formation algorithm should be *dynamic*. It should handle any topology changes during formation and throughout the operation of the scatternet.

II. *Isolation:* Initially, devices have no knowledge about their surroundings.

SOLUTION: A centralized scatternet formation needs extensive messaging and is practically inefficient. The failure of the center or any dynamic changes requires restart of the formation process. So, a *distributed* approach should be used.

[*] Multihop means that each node does not have to be in the transmission range of all other nodes.

III. *Power efficiency:* Since Bluetooth modules are used mostly by simple mobile devices, powers of these devices are supplied by batteries.

SOLUTION: So energy must be used efficiently. The scatternet formation procedure should use as few message exchanges as possible. Also role assignment should be done such that power is used as efficient as possible to increase the lifetime of the scatternet.

VI. *Small multihop networks:* Assuming that each Bluetooth unit is in the transmission range of the others requires the devices to be confined into an area smaller than $10\sqrt{2}$ x $10\sqrt{2}$ (class 3), which is a reasonable assumption for small conference meeting applications or personal area networks. But Bluetooth is considered as a promising technology for sensor networks where hundreds of sensors are spread over a larger area (due to improved security provided by frequency hopping). Also usage of Bluetooth technology in smart home applications may also require multihop scatternets.

SOLUTION: The scatternet formation algorithm should form multihop scatternets. A device being heard by a single scatternet member must be enough for it to be connected to the scatternet.

VII. *Topology:* Since each link must be built up before communication and the assignment of links is a critical issue in scatternet formation, topology of the formed scatternet is important. An active link means cost, on the other hand, establishing links only to part of neighbors may lead to longer paths (increasing cost) or even a situation where some of neighbors are unreachable.

SOLUTION: One extreme way is to establish links to all the neighbors so that every neighbor is reachable in one hop. The other extreme is to establish the minimal number of links yet guarantee the reachability where tree topologies are formed. There are also proposed interim solutions that create mesh topologies. The optimum solution to this problem is shown to be application dependent [11].

IV. *Delay:* One of the problems with scatternet formation is being time-critical. Scatternet formation operation should be completed as fast as possible looking from a user perspective.

SOLUTION: Delay of scatternet formation highly depends on the protocol. But proposed solutions show that it depends highly on the distributedness of the protocol and the method device discovery (inquiry/inquiry scan) is done. The more distributed and the less time required for device discovery, the faster the scatternet is formed.

3.1.2 Published Methods for Bluetooth Scatternet Formation

Studies related to Bluetooth scatternet formation can be separated into two groups. One group of studies concentrates on methods for scatternet formation while the other group concentrates on scatternet topology optimization.

The published methods for Bluetooth scatternet formation show differences in their approaches to some of the above problems:

I. *Isolation:* First studies tried to form scatternets by centralized approaches [2][3], which later turned out to be impractical and left their place to distributed scatternet formation studies.

II. *Multihop:* First published studies formed onehop scatternets [2-4][16]. Latter studies concentrated on multihop scatternets, owing to the emergence of applications that need connectivity over distances greater than the short radio range.

III. *Topology:* Until 2003, all of the formed scatternet had tree topologies [4-6]. New studies have started to investigate also star, ring and mesh topologies [7-10]. In [11], an analysis of Bluetooth scatternet topologies is made and the results showed that the optimum topology is application dependent.

IV. *Mobility:* Dynamicity of Bluetooth scatternet formation algorithm has not yet been addressed fully. [4] and [6] have investigated the time requested to reconfigure the scatternet after arrival of a group of nodes.

V. *Power-efficiency:* This problem has not been investigated yet for Bluetooth networks. Our study is the first in considering power efficient methods for scatternet formation.

VI. *Delay:* Scatternet formation delay has always been a parameter taken care in nearly all of the studies.

Instead of a distributed approach, a centralized approach is used in [2] and [3]. The formation algorithm in [3] 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.

A similar algorithm is the Bluetooth Topology Construction Protocol (BTCP) [2]. BTCP has three phases: (I) a coordinator is elected with a complete knowledge of all devices, (II) this coordinator determines and tells other masters how a scatternet should be formed, and (III) the scatternet is formed according to the instructions. This method addresses the problem of scatternet formation however it has some disadvantages. Firstly, it is a centralized approach and shares the drawbacks described in the previous section. If the coordinator fails, the formation protocol has to be restarted. BTCP is not suitable for dynamic environments where devices can join and leave after the scatternet is formed since there is no efficient method how to recalculate the network topology.

BTCP's timeout value for the first phase would affect the probability that a scatternet is formed.

LMS is a distributed formation algorithm that is similar to BTCP [16]. LMS uses one phase and overcomes the timeout problem. Since the protocol's timeout value for each round affects the overall performance of the protocol—the scatternet is formed with certainty. This algorithm also has the drawback of forming onehop networks.

The shortcoming of all the above protocols is that it assumes a onehop network, where every node should be in the radio range of all others. The rest of the protocols produce multihop scatternets.

Among these, the protocols resulting in tree topologies are: Tree Scatternet Formation (TSF) protocol [4], Bluetree [5] and Shaper [6]. TSF and Shaper dynamically reconfigure the scatternet after topological variations, but TSF is a onehop scheme.

Bluetree [5] is a practical protocol for forming connected scatternets, which has two variations, namely, *Blueroot Grown Bluetree* and *Distributed Bluetree*. The former builds a scatternet starting from some specified node called *Blueroot*, while the latter speeds up the scatternet formation process by selecting more than one root for tree formation and then merging the trees generated by each root. One distinct feature of the Bluetree scheme is that all resulting scatternets assume a topology of spanning tree, where the parent node is master and the children nodes are slaves. Though the scheme selects the smallest possible number of links to form a connected scatternet and tries to spend the least of network resources on maintaining the scatternet, the resulting scatternet has inherent deficiency due to its hierarchical structure. First, it lacks reliability. If one parent node is lost, all the children and grandchildren nodes below it will be separated from the rest of the network and part of the tree or even the whole tree has to be rebuilt in order to retain the connectivity. In a mobile network, this may happen quite frequently, making the Bluetree very susceptible.

Another class of multihop proposals define algorithms that produce connected scatternet by exploiting clustering schemes for ad hoc networks. *BlueStars* [7], *BlueMesh* [8] protocols and [9] generate mesh scatternets with multiple paths between any pair of nodes. *BlueMesh* and [9] allows each master to select at most 7 slaves. [9] assumes that each node knows its position and that of its neighbors which is impractical for Bluetooth applications.

The group of studies that concentrate on scatternet topology optimization are [11] and [17-20]. This issue is faced in [18] and [20] by adopting centralized approaches. In [18], the aim is minimizing the load of the most congested node in the network, while [20] discusses the impact of different metrics on the scatternet topology. A distributed approach based on simple heuristics is presented in [19]. The results of [17] reveal some important performance implications of scatternet design decisions serving guidelines for scatternet formation algorithms.

3.1.3 Important Aspects of SF-DeviL

None of the above scatternet formation methods considers energy efficiency which is especially important in the operation and lifetime of the formed scatternet. Energy efficient techniques in routing protocols for Bluetooth scatternets have been investigated, and it is shown that a considerable gain in network life can be achieved by using distance based power control and battery level based master-slave switch [12]. But such techniques are not considered for formation or operation of scatternets.

Energy efficiency becomes very important for tree scatternet topologies, where the root node and nodes closer to the root need to handle significant transit traffic and thus may run out of battery.

SF-DeviL algorithm takes care of energy efficiency at scatternet formation procedure and throughout the operation of the scatternet. The most important aspects of SF-DeviL can be summarized as following, where the first three properties of SF-DeviL serve for energy efficiency, while the last serves for connectedness.

SF-DeviL,

- ✓ *Uses 'class of device' information, i.e. assigns roles to nodes by looking whether it is a laptop, a PDA, a sensor etc.*
- ✓ *Measures received signal strength and quantizes it; and establishes links giving priority to shorter links.*
- ✓ *Keeps track of battery levels throughout scatternet communication and re-arranges the scatternet so that 'busy' nodes have more energy.*
- ✓ *Unlike other scatternets formation methods, slaves choose their masters. By this way, the possibility of unconnectedness is eliminated.*

Briefly, by considering the device and link characteristics and keeping track of battery levels, SF-DeviL increases the robustness of the scatternet in dealing with topology changes and battery depletions.

Chapter 4

SF-DeviL

SF-DeviL (Bluetooth *S*catternet *F*ormation algorithm based on *Devi*ce and *L*ink characteristics) is an *energy-efficient*, *distributed* and *dynamic* algorithm for the formation of Bluetooth *multihop*, *tree* structured scatternets. SF-DeviL is not only a scatternet formation algorithm, but also a scatternet maintenance algorithm that runs throughout the lifetime of the scatternet. Description and a detailed investigation of the features of SF-DeviL are given in this chapter.

4.1 Motivation

The main objective of SF-DeviL is energy-efficiency. Bluetooth units are mostly used by mobile devices, and energy is supplied by batteries that have limited lifetime. Battery depletion results in failure of the node, which is an unwanted situation looking from a user perspective, and also it may require reorganization of the whole scatternet.

Besides this main objective, SF-DeviL is aimed to run in a distributed manner, to adapt to changes of topology, to handle multihop operation and to ease routing by choosing appropriate topology.

SF-DeviL uses two parameters, which are particular to the algorithm, to achieve these goals: Device Grade and Received Signal Strength Grade.

4.1.1 Device Grade

SF-DeviL uses the class of the device that the Bluetooth module is embedded onto in the scatternet formation, i.e., scatternet is formed by taking into consideration whether the device is a laptop, a desktop or a PDA etc.

Device class is known to Bluetooth module and is exchanged with neighboring devices during connection establishment procedure by the class of device/service field of the frequency hop synchronization packet explained in Section 2.3.2. Battery capacity and traffic generation rate of a node can be predicted using class of the device information.

Since master and bridge nodes are loaded more compared to slaves, a device with a high battery capacity and high traffic generation rate is better to be chosen as master or bridge. If a device, having a high battery capacity and is likely to generate high traffic, is chosen to be a master or a bridge, the resulting scatternet will be more stable and energy-efficient. For example, for the scenario illustrated in Figure 4.1, choice of a mobile phone as the master of several laptops is not an intelligent decision for a robust network for several reasons:

1. A mobile phone has lower battery capacity than a laptop so it might run out of battery requiring reorganization of the scatternet.
2. A mobile phone is possibly more mobile than a laptop. Position change of a master requires a more difficult rearrangement of topology than the movement of a slave.

3. Since a laptop generates high rate traffic, the mobile phone has to spend its resources to forward packets from one laptop to the other. Having a high traffic generation rate device as a master is a better choice.

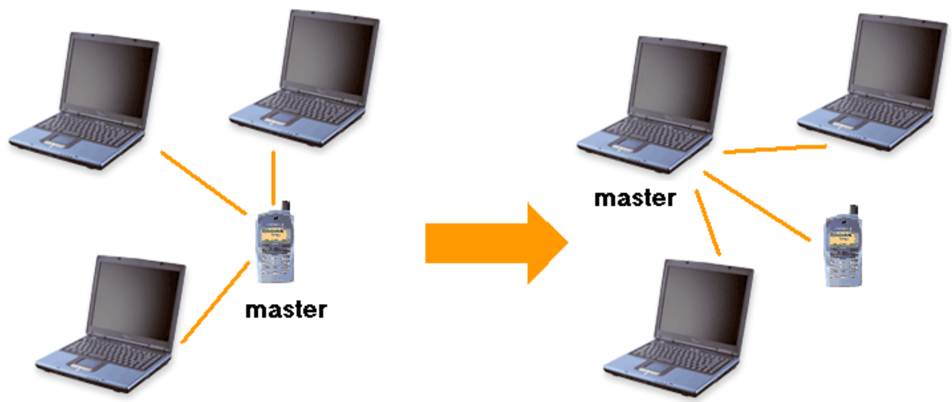


Figure 4.1: Piconet (scatternet) formation based on device characteristics

Not only the battery capacity, but also the battery level of a device is important in the assignment of roles to nodes. A device with a high battery capacity but a low battery level is not a good candidate for master or bridge role.

SF-DeviL assigns a Device Grade (DG) to each node to make use of the class of device information together with battery level of devices. DG is calculated using device classes and the battery level.

$$DG = \alpha * BatteryCapacity * BatteryLevel + (2-\alpha) * TrafficGenerationGrade \quad (1)$$

$$(1 \leq \alpha \leq 2)$$

where α is used to assign relative weights for battery and traffic terms. α is also a variable depending on battery levels as explained in section 4.3.2.1. BatteryCapacity (BC) indicates the power capacity of the battery, and the BatteryLevel (BL) represents the fraction of remaining battery.

TrafficGenerationGrade (TGG) is a prediction of traffic generation rate of the device which is obtained from class of the device. Devices with larger and/or fuller batteries and higher traffic generation rate are assigned larger DGs.

Although mobility of devices is not explicitly shown in the formulation in (1), it is hidden in the power term. A stable device, such as a desktop, printer, scanner etc. is fed from the power line instead of batteries. Thus, battery capacity of stable devices is the maximum and the battery level is always equal to 1. For this reason, a stable device is assigned a large DG that does not change throughout scatternet lifetime (due to non-decreasing battery level).

4.1.2 Received Signal Strength Grade

Bluetooth modules have power control abilities [1]. If devices receiving strong signals from each other are connected, less power is consumed for transmitting signals, thereby increasing the lifetime of the scatternet and reducing interference as illustrated in Figure 4.2.

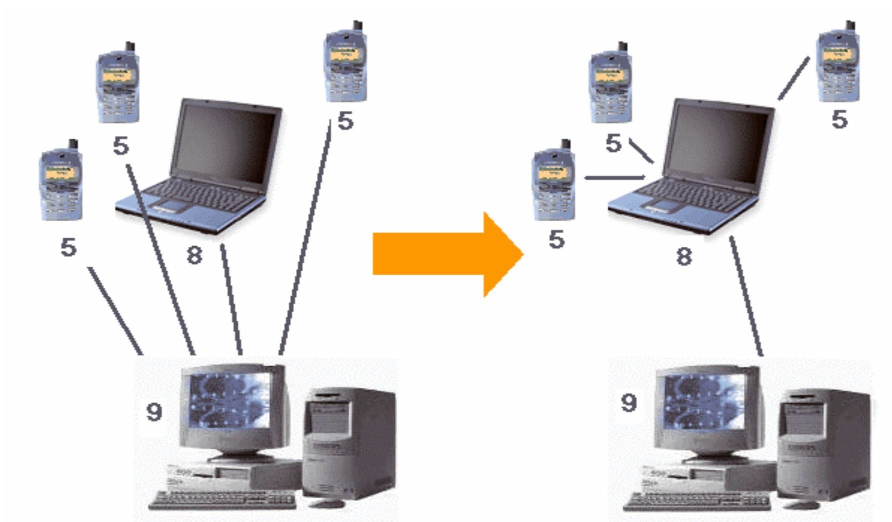


Figure 4.2: Scatternet formation based on link characteristics

Bluetooth module has Received Signal Strength Indication (RSSI) that measures the received signal strength [1]. Each device assigns a Received Signal Strength Grade (RSSG) to each neighboring device based on the measured RSSI for that link. SF-DeviL uses RSSG to construct the scatternet in such a way that the links are established between closer nodes in the formed scatternet topology. RSSG is quantized according to strength of the received signal as:

1. Weak (W): RSSG=1
2. Medium (M) : RSSG=2
3. Strong (S) : RSSG=3
4. Very strong (VS) : RSSG=4

4.2 SF-DeviL Algorithm

SF-DeviL is a two-phase algorithm, where some of the nodes undergo phase 2:

I. In the first phase, procedure *MAIN* is executed by each node. During the first phase, each node seeks the 'best master' for itself, i.e. *each slave chooses a master*. The best master is chosen by making a comparison between the ex-master and newly connected master by using *BestMaster* procedure. During this phase, each node continuously tries to discover other devices, establishing a link to a better master and deleting the older link until a discovery timeout (discoveryTO) is reached.

II. In the beginning of the second phase, each device has found a master and connected to it, or it has declared itself as root of the scatternet. Thus, in the second phase each node that declares itself as root runs the *Semiroot* procedure. By the Semiroot procedure the disconnected trees are merged into a single scatternet. The Semiroot procedure ends when all roots are connected.

4.2.1 MAIN Procedure

SF-DeviL is a distributed algorithm where each device X upon initialization starts the MAIN procedure given below in Table 4.1:

```
MAIN:
Upon initialization, calculate DG(X)
do {
    Alternate between I / IS until a device Y is discovered
    Establish link to Y
    Add BD_ADDR(Y).DG(Y).RSSG(Y) to neighbor_list(X)
    If  (Y==BestMaster(master of X, Y) )
        Update route tables (delete ex-master link)
        Do master/slave switch (if X is inquirer)
    else
        Request Y to disconnect from it.
} while (discoveryTO not reached)
```

Table 4.1: MAIN Procedure of SF-DeviL

Device X, upon initialization, calculates its DG(X) by using its class of device and its battery level indicator using (1). The BatteryCapacity and TrafficGenerationGrade corresponding to the class of the device are determined from a table that is embedded into the Bluetooth module.

Device X has the objective of finding itself a master. But the master of X has to meet some requirements. First of all, it has to have a DG $\geq$ DG(X). X and the master candidate must exchange their DGs to make a comparison. DG is be carried by FHS packets*.

X starts alternating between inquiry and inquiry scan states until it discovers a device Y. For the moment assume that X discovers Y, meaning that X is the inquirer and Y the inquiry scanning device. For both X and Y to exchange FHS packets, they have to establish a link. Thus, in line 4, X-Y link is established. X becomes the master since it was the inquirer (see section 2.5.2).

The FHS packets exchanged provide both devices the DG of each other. Furthermore, during link establishment, both devices measure the received signal strength of each other obtaining RSSG of that link. Also since BD_ADDR is contained in a FHS packet, both devices get each other's addresses.

Each device constructs a list of its discovered neighbors by adding the discovered devices to its 'neighbor_list'. In the neighbor_lists the BD_ADDR and DG of the discovered neighbor is stored together with the RSSG of the link to that neighbor as shown in Figure 4.3. The entry Y of neighbor_list(X) is the Bluetooth device address of Y, followed by DG and RSSG of Y.

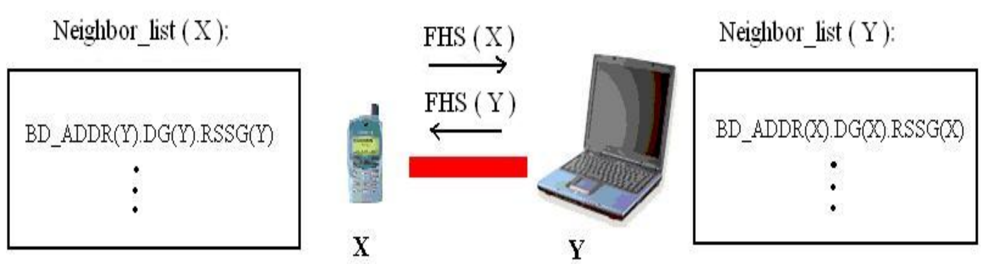


Figure 4.3: Neighbor_list construction

* The class of device information is already carried by FHS packets. DG is calculated using class of device and batter level of device. The battery level information can also be carried by FHS, since FHS has some reserved bits as mentioned in section 2.3.2. An undefined field of FHS of 2 bits, 2 bits in major device class and at least 1 bit in minor device class is not used, which constitute a total of 5 bits.

BestMaster procedure in line 6 is used to evaluate if the new discovered device Y, is a "better" master for X. Although X has become the master of Y after link establishment, X checks if Y could be a better master for itself. The BestMaster procedure determines the best master by comparing the ex-master with the new one, which is described in the next section.

If Y is a better master for X, X deletes the link to its ex-master (if there existed one) and the route tables of descendants and ascendants of X are updated (firstly deleting the ex-link information from route tables, secondly adding the X-Y link information to route tables). Furthermore, since X has decided that Y is a better master for itself *but* X is the master, X and Y do a master/slave switch (see section 2.5.3). This is done for assigning slave role to the leaf nodes, master/slave bridge role to the intermediate nodes, and master role to the root.

If Y is not a better master for X, X reports Y that it wants to delete the newly established X-Y link in line 10. Y also runs procedure MAIN synchronously as the inquiry scanning device. If X is not the best master of Y, determined by BestMaster(*ex-master of Y, X*) , then Y also requests to disconnect from X. The device that first gets the 'disconnect request' and has a similar request deletes the link. Conversely, Y may have chosen X as its best master. In this case it reports back not to delete the link.

SF-DeviL limits the number of slaves < 7 for each node, reserving one link to the master. There may exist situations where the selected master already has maximum number of slaves. In such a case, this master deletes its 'worst' slave. The slave with the smallest DG+RSSG value is the worst and is requested to look at its neighbor_list for a new master. If there are some master candidates for that worst slave, the worst slave link is deleted, else the second-third... worst slaves are considered for deletion.

X stops procedure MAIN until it does not discover a new neighbor for a specific timeout (DiscoveryTO). After completing MAIN, X has either found a master and connected to it, or has declared itself as a 'semiroot'. The term *semiroot* is used to identify the state of devices that have selected themselves no master, *think that they are a root, but are not sure yet*. A semiroot may be the root of a disconnected tree, a free node or the root of the whole scatternet.

4.2.2 Best Master Selection

BestMaster (ex_master, new_master) is the procedure to find out which device is the best master for X: the ex-master of X or the newly discovered and connected device. The BestMaster procedure is given in Figure 4.4.

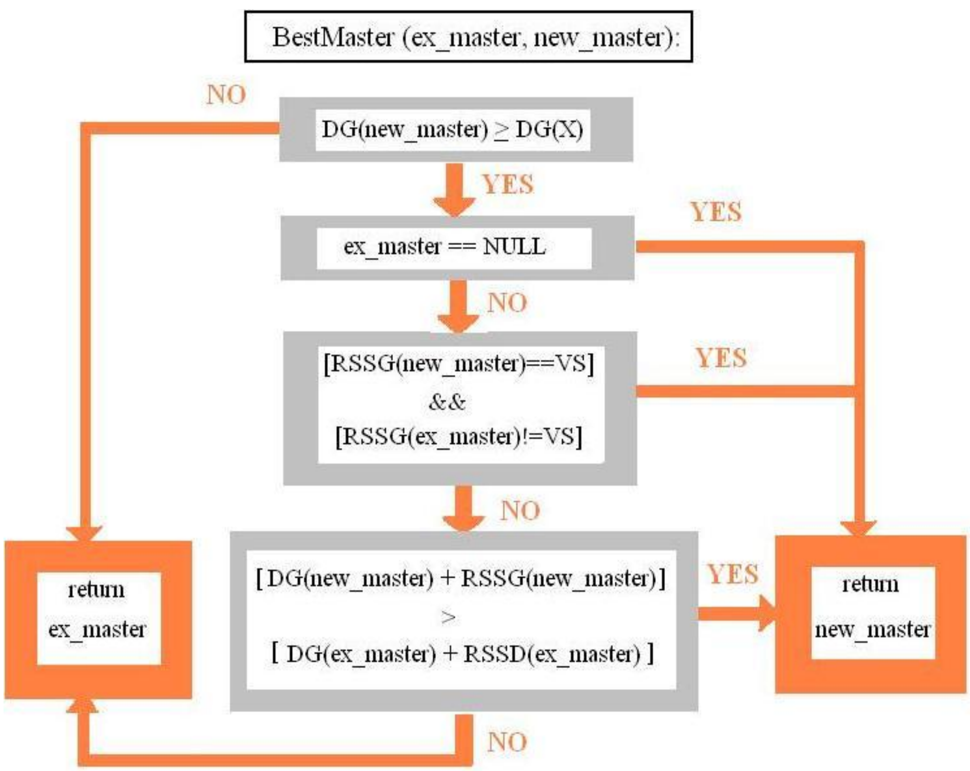


Figure 4.4: Best Master Selection

The master of X must have a larger or equal DG than X: Since DG is an indication of 'strength' of the device in terms of power and traffic generation rate, a master is selected only if it is stronger than or equivalent to its slave.

When DG's are equal, the device with fewer number of slaves or smaller BD_ADDR (in case of equal number of slaves) runs BestMaster procedure*. Equal DG devices can run this procedure. This is done to avoid waste of resources for scenarios when all devices are of the same class and with same battery levels-having the same DG. In such a scenario no one would choose a master if DG>DG(X) is not relaxed to DG≥DG(X). Thus, the first phase would end with no links at all. The equal sign avoids such a situation.

RSSG=VS has priority over other links: A link where a very strong signal is received is preferred. 'Very Strong' is suggested to be taken as the path loss at reference distance**. This ensures that power control is done such that the RSS is kept at its lower bound (see section 2.6, Figure 2.12).

DG is not used solely as a criterion. The master with the larger sum of RSSG and DG deserves to be the master. By this rule, a weighted sum of 'length of links' and 'strength' of devices is compared. A closer PDA is chosen to be a better master than a far away desktop, since less power is used to transmit packets and interference is reduced.

4.2.3 Semiroot Procedure

After completing MAIN, as mentioned before, X has either found a master and connected to it, or has declared itself as a semiroot. In the second phase of SF-DeviL, X runs the Semiroot procedure in Table 4.2. By this procedure, X finds out if it is really the root, and if not, connects to other semiroots. *Only semiroots*

---

* If both devices run BestMaster Procedure they will select each other as master, forming an unnecessary loop. The number of slaves can be exchanged by AM_ADDR field of FHS packet, which is currently used as all zeros for FHS packet.

** In our simulations, we took the reference distance as 1m. where the path loss is 30dBm. Meaning that, signals that have path loss lower than 30dBm are considered to be very strong(VS).

run this procedure, i.e. the devices that have not found a master. Thus, at least one device runs the Semiroot procedure.

The detailed description of line 2, how semiroot X checks weather any unconnected but heard nodes exists, is done as follows:

1. X generates a packet named ‘member_list(X)’ which contains the BD_ADDRs of all the members of the tree and floods this packet downwards to all members of the tree.
2. All members of the tree, including X, compare their neighbor_lists with member_list(X). If there is any node in any of the neighbor_lists, which does not exist in the member_list(X), i.e. any unconnected but heard node, this node is reported back to X.
3. Each member has to report back to semiroot, even if the report is NULL.
4. If the number of NULL reports that reached X, is equal to one less of the member number, i.e. no unconnected node exists, X declares itself as root and Semiroot procedure ends (lines 8-9).
5. At least one non-NULL report means that the scatternet is not formed yet and X is a semiroot.

Semiroot:

```
1   Start after MAIN.
2   Check if any unconnected but heard node exists
3   If any unconnected node exists
4           Alternate between P/PS  for at most pagingTO
5           If connection established
6                   Execute lines 5-10 of MAIN
7                   Go to line 2
8   else
9           exit
```

Table 4.2: Semiroot Procedure of SF-DeviL

In line 4, if any unconnected node exists, X alternates between page and page scan modes. It pages all the nodes with DG ≥ DG(X) one by one and enters PS periodically. Each time X connects to any of the other semiroots, it executes the lines 5-10 of MAIN. The two connected semiroots decide on which one to become the master by the same BestMaster procedure.

After each connection establishment, i.e. merging of trees, X goes to line 2, to check unconnected nodes, since the new link may have formed the scatternet or brought new unconnected but heard devices.

X may not be able to establish connection with any of the paged devices and may not be paged for a specific paging timeout (pagingTO), meaning that *X is not in the communication range of the seeked devices* or *the once heard devices are gone*. In this case, if X has a master (X may have a master after merging trees), it gives up Semiroot procedure and reports the unconnected devices to the root (or semiroot) of its tree. But if X has no master, i.e. it is the semiroot of the tree, in this case X orders its members to page the unconnected but heard devices. All the members of the tree page these devices in cooperation (also do PS alternatively) for pagingTO. If an unconnected device is found by a member of tree a connection is established through that member. If no device is found X declares itself as root and SF-DeviL terminates.

4.3 Features of SF-DeviL

SF-DeviL runs in a distributed fashion where each node runs MAIN and then the disconnected tree roots (semiroots) run Semiroot procedure. SF-DeviL forms energy-efficient, multihop scatternets with tree topology where *the root is the master, all the intermediate nodes are M/S bridges and the leaves are slaves.* SF-DeviL is appropriate to handle battery level changes and dynamic environments. This section explains how the above procedures provide these features.

4.3.1 Energy Efficiency

The BestMaster selection rules guarantee that each device has a slave that has a larger or equal DG than itself. Also each device is allowed to have a single master. Thus, the resulting scatternet has a tree topology where the devices with larger DGs are assigned as the root and bridges, and the devices with smaller DGs are assigned as leaves.

The use of received signal strength through RSSG, gives priority to links that have lower path loss. For indoor environments, the establishment of a RSSG=VS link reduces the transmission power from 1 mW to about 0.001mW for class 3 devices, providing a 99.9% reduction in energy dissipation.

4.3.2 Scatternet Maintenance with SF-DeviL

SF-DeviL is does not only form the scatternet, but also does the maintenance of it. Scatternet maintenance by SF-DeviL has two forms:

4.3.2.1 Maintaining Battery Level Changes

The goal of satisfying energy efficiency in a network requires avoidance of battery depletion of a Bluetooth device, looking from user perspective. In a tree topology, this issue becomes a larger problem since the root node and its children carry most of the traffic and run out of power.

The battery level information of each device is used to calculate its DG (1). Also α is a function of the BatteryLevel (BL):

$$\alpha = (BL-1)^2 + 1 \qquad (0 \leq BL \leq 1) \qquad (2)$$

As communication takes place in the scatternet BL of each device decreases, some BLs decreasing more rapidly. The decrease of BL, decreases power term of DG and increases α. The increase of α changes the weights for power and traffic terms. As a result as, the more BL decreases the more weight given to power term. This is done to avoid battery depletion of very low battery level devices.

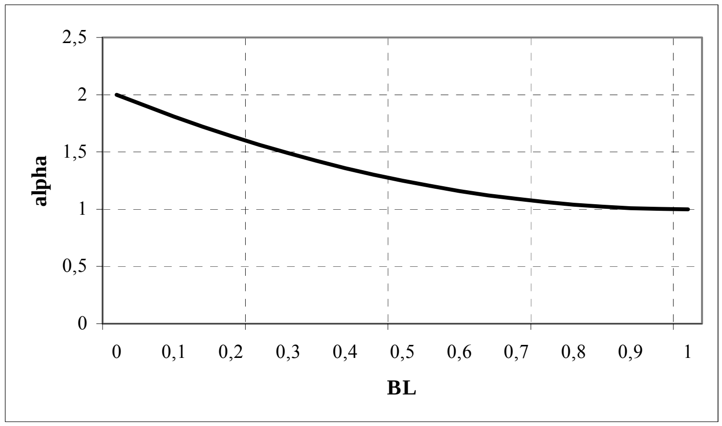


Figure 4.5: Relation of α and BL

SF-DeviL is restarted when battery levels are depleted. If BL of a device reaches a threshold value (BLthreshold), the device requests the root to restart scatternet formation. The root orders all members to re-calculate their DGs and report to the root. After the root collects the updated DGs from all members, it sends a 'BLScatUpdate' packet to all members. The BLScatUpdate (*BL* based *scat*ternet *update*) packet includes BD_ADDR and DG of all tree members. Any member X that receives this packet restarts the Semiroot procedure given in Table 4.2 with two modifications:

1. Before Semiroot procedure, each X deletes its master link if DG of its master is smaller than its own DG, i.e. DG(X) > DG(master of X).
2. Replace 'unconnected but heard devices' in lines 2&3 with 'devices with DG ≥ DG(X)'.

Each device X has chosen the best master, after running the Semiroot procedure with the above modifications. This way the devices with decreasing battery levels are pushed downward towards the leaves in the tree.

4.3.2.2 Maintaining Topology Changes

SF-DeviL scatternets are appropriate to work well in dynamic environments where nodes move around, addition and deletion of nodes occur.

DELETION: A master that has polled slave X a specific number of times and has received no reply starts P/PS that node during its empty slots. If no reply is obtained, the deletion of X is reported to related nodes that have X in their route tables.

Any node that has lost connection from an SF-DeviL scatternet, does P/PS where it first pages its master (for pagingTO). If X can not find its master, it then pages any entry in its neighbor_list with DG>DG(X). If no connection is established, X starts I/IS returning to MAIN procedure.

ADDITION: The leaf nodes of a tree are the nodes that have the lowest traffic load. They do not switch between piconets like the bridges or do not forward packets like the root. The leaves, as any slave does, reply the polls of master and spend the remaining slots in standby mode.

Thus, in highly dynamic environments, leaf nodes can be assigned the duty of device discovery by running I/IS to let addition of new nodes. This device discovery duty can be done in various ways. An energy-efficient way is considered to be like this: Each master of leaf nodes may let only one slave to do device discovery. This slave is the one with the largest DG among its slaves. The master can choose with BL probability to assign this duty, where BL is the battery level of the largest-DG-slave.

This situation is made clearer in Figure 4.6. The leaf masters in this scatternet are A, B and C, where B is the root node. A is the master of a1, a2, a3, a4 and a5. Among these devices, A chooses the device with the largest DG to give the device discovery duty. Let's say that the largest DG belongs to a1, DG(a1). Node A gives this duty to a1 with a probability of BL(a1). Let's say that after some time, DG(a1) decreased below DG(a2). Thus, A takes the duty from a1 and gives it to a2 with probability BL(a2). By this way, some nodes of the scatternet (a1, b2 or c3 for example) execute device discovery with a probability depending on their battery levels.

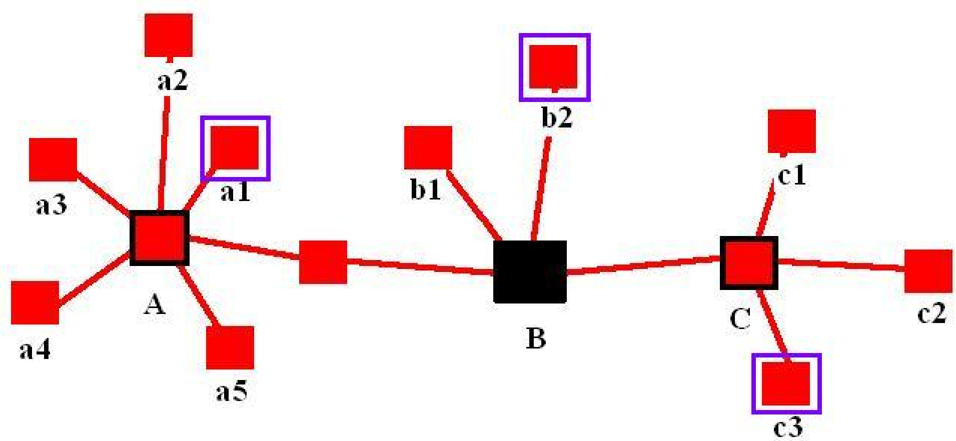


Figure 4.6: Illustration of ongoing device discovery by selected leaf nodes to provide node additions

4.3.3 Multihop Support

Each device forms a neighbor_list of the discovered devices. Also the semiroot procedure in Table 4.2 does not terminate until any heard but unconnected device is connected to the scatternet. Thus, a device X that is heard by at least one of the members of a scatternet is at the end connected to the scatternet. It is enough for a device to be in communication range of at least one of the members of the scatternet and there is no requirement for a device to be in communication range of all other devices.

In Figure 4.7.a, an extreme case of node locations is given, where nodes located on a straight line and separated by a distance equal to the range. These nodes cannot be united by a onehop network, i.e. a multihop scatternet should be formed. In Figure 4.7.b, the neighbor_lists of the nodes are given. By the MAIN procedure devices A and C choose B as their master, since DG(B) is larger than their own DGs. At the end of MAIN, B and D have declared themselves as semiroot, since their DG is better than any discovered device. By the semiroot procedure, B finds that D is a heard but unconnected device and starts paging D. Meanwhile the free node D, finds that C is a heard but unconnected device and pages C. Since D is not in communication range of B, B can not find D. As stated in section 4.2.3 after pagingTO, B orders C (the node that has C in its neighbor_list) to page D. Now that C and D both do P/PS, a link between C and D is established. Figure 4.7.c illustrates the resulting scatternet formed with SF-DeviL, where B is the master, C a M/S switch, A and D slaves.

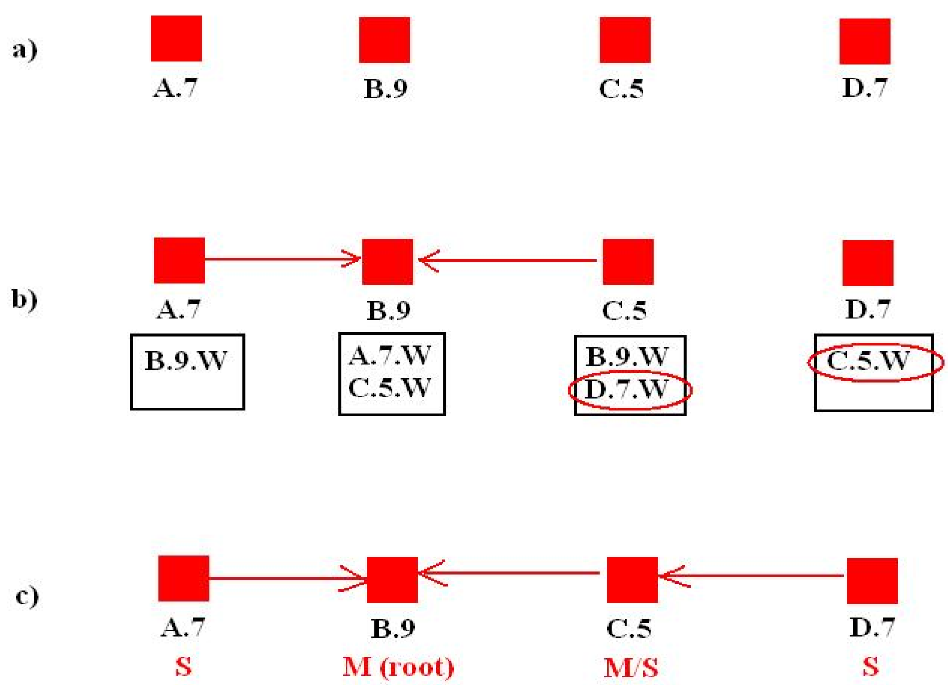


Figure 4.7: Illustration of an extreme example for multihop support of SF-DeviL: a) Node locations where the distance between nodes is equal to range of devices. The label denotes BD_ADDR and DG of each node. b) Neighbor_lists of each node. c) Resulting scatternet.

4.3.4 Tree Topology

SF-DeviL scatternets result in tree topologies. A tree topology has a number of advantages:

I. With a tree-like structure, the scheduling algorithm and the ad hoc routing schemes become simpler.

II. Furthermore, network re-configuration can be easily obtained via merging of trees.

III. Finally, the distribution of network control information is straightforward. If control and management information is to be efficiently disseminated in the network, a broadcast-like facility is needed to quickly deploy. To this aim, a tree topology may be very convenient, if two key conditions are met: i) the network is easily reconfigurable after nodes have joined or left the system; ii) the scatternet formation or reconfiguration delay is within a reasonable amount of time.

A tree topology on the other hand has some disadvantages:

I. Since any couple of nodes is connected via a single path, some nodes can become bottlenecks. The root node and nodes closer to the root node are very likely to become communication bottlenecks.

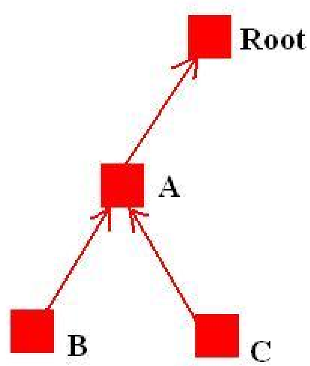
II. Furthermore, it lacks efficiency in routing because all the routing paths have to traverse the tree in upward and downward directions. This becomes even worse in a larger system.

SF-DeviL scatternets, where devices of different classes are collected, the second disadvantage is eliminated partially because of the TrafficGenerationGrade in DG. SF-DeviL tends to place devices that generate high rate traffic closer to the root of the tree. Thus, most of the packets traverse a shorter path. But in situations where all devices are of the same class, this disadvantage remains.

4.4 Routing in SF-DeviL Scatternets

Routing in SF-DeviL scatternets is done via route tables that are constructed during SF-DeviL. Each added or deleted link is reflected to route tables of that branch of the tree.

Each entry of a route table consists of the *BD_ADDR of the entry*, *BD_ADDR of the node through which this entry is reached* and *the number of hops to that entry* as illustrated in Figure 4.8:



Route table of Root:

A	-	1
B	A	2
C	A	2

Figure 4.8: Route table entry of a node in SF_DeviL scatternets

A route table of a node has all descendants of that node. A packet is routed downwards to descendants if the destination exists in the route table. If the destination does not exist in the route table, it is routed upwards to ascendants. Each ascendant first checks if the destination exists in its route table, if not goes on forwarding upwards until to the root. The root forwards the packet to its destination.

Chapter 5

SIMULATIONS AND RESULTS

We developed a C++ based simulator based on the Bluetooth specifications [1]. The performances of SF-Devil and LMS [16] are compared using this simulator. LMS is used for comparison because it is easy to implement and it is a protocol that ensures that the formed scatternet is connected. LMS also results in tree topologies like SF-DeviL.

This chapter includes a description of assignment of some parameters and simulation results.

5.1 Assignment of Some Quantities

Nodes are randomly distributed in an area of 10mx10m and are assigned random device classes where all of the devices are battery fed. The batteries are assumed to be initially full. The average of five randomly generated node locations and traffic patterns are used in order to compare performances of SF-DeviL and LMS.

5.1.1 I/IS State Transition Parameters

All devices are assumed to start I/IS at the same time for device discovery. The inquiry and inquiry scan procedures of connection establishment procedure requires some assignments of how the state transitions should be done and how long each state should last. The number of responses and inquiryTO (explained in section 2.4.2) that terminates inquiry substate, should be decided.

In our simulations, we took the number of responses as 1 to ensure that each discovered device is connected (to exchange FHS packets). Also inquiryTO is taken as equal to discoveryTO (mentioned in Table 4.1).

The parameters related to the state transitions during I/IS procedures affect the scatternet formation delay. We assumed that I/IS state transitions follow the pattern shown in Figure 5.1. The interval length of any state is a uniform random variable with the interval given in Table 5.1.

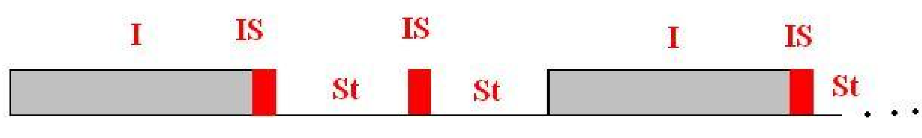


Figure 5.1: I/IS procedure state transitions used in simulations

States	Interval Lengths
I	[1.28sec-5.12sec]
IS	[11.25msec-40msec]
St (Standby)	[0.64sec-2.56sec]

Table 5.1: Intervals of the states in I/IS procedure

For IS, we used R1 mode where the unit enters standby state after each IS period. During SF-DeviL, the connection set up to a device may be deleted after a few slots (if this link is not a best master link). In such a case, maintaining the IS state may end up with re-discoveries to the same device. The standby mode is necessary to ensure that in such a case, the same unit is not discovered again and again.

5.1.2 Path Loss Model

We used the path loss model:

$$PL(d) = PL(d_0) + 10\,\gamma\,\log(d/d_0)\ ,$$

where $PL(d_0 = 1m) = -30dBm$, and $\gamma = 2.5$.

5.1.3 Power Control Parameters

Power control is done after completion of procedure MAIN. Power control is done at each node so that the received power level is kept at –60dBm, which is the average of the bounds for lower level of RSSI (Figure 2.12).

In our simulations, we used class 1 Bluetooth units, which have maximum transmission power of 0dBm . The transmitter power is controlled, where it has a dynamic range which extends from 0dBm to –30dBm in steps of 2dB [1].

In our simulations, the power consumed for transmission/reception of each packet is given by

$$P_{per\_packet} = P_{standby} + P_x\ ,$$

where P_x is $P_{transmit}$ for transmitters, $P_{receive}$ for receivers and P_{inter} for intermediate nodes. $P_{standby}$ is the power consumed in the standby mode. We assume that the following relations hold between these parameters:

$$P_{standby} = P_{receive} = P_{transmit} / 316$$

$$P_{inter} = P_{receive} + P_{transmit}$$

5.1.4 Assignment of Device Grades

DG is calculated by using the assigned TrafficGenerationGrade (TGG) and BatteryCapacity for different classes of devices, shown in Table 5.2.

Traffic Generation Grade (TGG)	Average traffic generation rate(bits/sec)	Device Class
5	1M	NAP
4	100k	projector, camera, computer
3	10k	printer, PDA, scanner
2	1k	headset, mobile phone, peripherals
1	0,1k	sensor
BatteryCapacity	**Lifetime if active (hours)**	**Device Class**
5	infinite	NAP, desktop, projector, printer, scanner
4	4	camera, laptop
3	3	Mobile phone
2	2	PDA
1	1	peripherals, headset, sensor

Table 5.2: Assignment of TGG and BatteryCapacity

These assignments are based on rough estimations, where TGG is predicted from the average traffic generation rate and BatteryCapacity is predicted from the average lifetime of the devices in terms of hours.

Using TGG and BatteryCapacity from Table 5.2, together with the battery level indicator of devices, DG of each device is calculated by (1).

5.1.5 Assignment of Received Signal Strength Grades

In our simulations, we used a simple path loss model, where randomness is not considered. Thus, the received signal strength quantization is made based on distance:

- $0 \leq d \leq 1m. \Rightarrow$ RSSG=VS
- $1m. \leq d \leq 4m. \Rightarrow$ RSSG=S
- $4m. \leq d \leq 7m. \Rightarrow$ RSSG=M
- $7m. \leq d \leq 10m. \Rightarrow$ RSSG=W

5.2 Simulation Results

The time at which the first device battery depletes, number of piconets, network diameter, average number of hops between any pair of nodes and scatternet formation delay are used as the performance metrics. The effects of changing DiscoveryTO on SF-DeviL performance are investigated. Scatternet maintenance by changing battery levels is simulated.

5.2.1 Average Lifetime of the Scatternet

Lifetime of the scatternet is defined as the time at which the first device runs out of battery. At each node traffic is generated randomly with a rate proportional to the TrafficGenerationGrade of the device. The devices are assigned full batteries initially. Assuming an average throughput of 300Kbps per node, the average lifetime is given in Figure 5.2 as a function of the network size.

Since devices with higher DG are assigned as the root and bridges, and links are established between closer nodes, scatternets formed with SF-DeviL carry more traffic than LMS before the first battery fails. Naming the time at which the first battery depletes, as lifetime of the scatternet, SF-DeviL scatternets have a larger lifetime than LMS. The lifetime of the scatternet formed by SF-DeviL doubles LMS for small number of nodes and becomes four times that of LMS as number of nodes increases. Lifetime of SF-DeviL scatternets show much or less the same behavior for different discoveryTO values. Large discoveryTO means longer inquiry/inquiry scan intervals and more battery dissipation during discovery, which lessens the lifetime. On the other hand, with a small discoveryTO, where less devices could be discovered, a scatternet topology far away from the optimum is formed that in turn decreases lifetime.

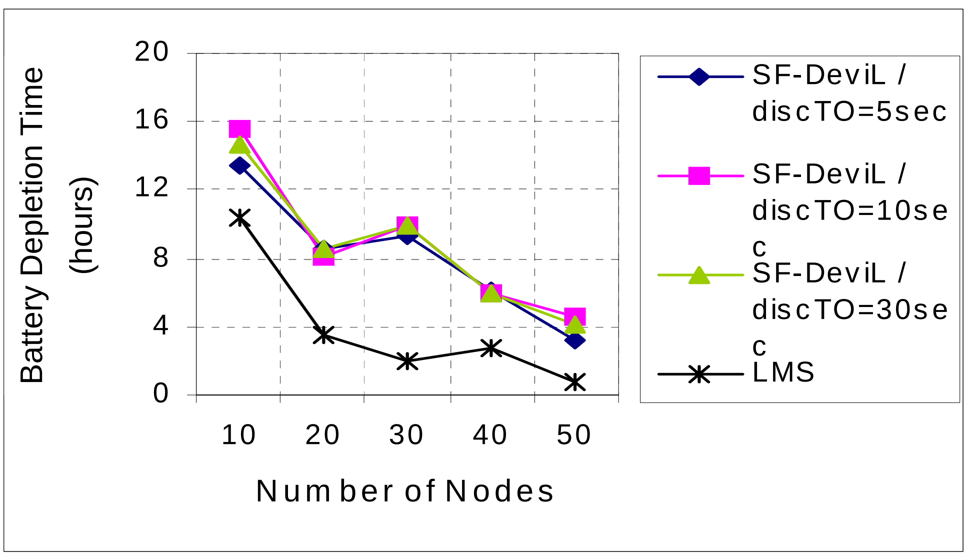


Figure 5.2: Time until the battery of first device depletes

The overall decrease in lifetime with increasing network size is because of the increase of average number of hops between source-destination pairs as shown in Figure 5.8. As the number of nodes increases, a packet reaches its destination in expense of decreasing the battery of *more* intermediate nodes. Thus batteries of bottleneck nodes are depleted faster as the scatternet grows.

5.2.1.1 Average Lifetime with Scatternet Maintenance

Scatternet maintenance by changing battery levels is available in SF-DeviL scatternets (as described in section 4.3.2.1). When the battery level of a scatternet node reaches a threshold, SF-DeviL is re-initiated. In the simulations, we took this threshold as ½.

We also added an additional local control to restart SF-DeviL: Each node having BL ≤ ½ also checks the DGs of its slaves. If any DG(slave) > DG of itself, only then SF-DeviL is initiated.

We used two cases as an initiator for scatternet update:

I. CASE-1: [BL ≤ ½]

II. CASE-2: [BL ≤ ½] & [DG(at least one slave)> DG]

The scatternet updates increases the average lifetime of scatternet for all discoveryTO values as shown in Figures 5.3 and 5.5. The average lifetime for CASE-1 and CASE-2 is about 2-6 times of the average lifetime of SF-DeviL where no scatternet updates take place. The increase in lifetime is more visible for large number of nodes for both cases.

The additional control that takes place in CASE-2, increases the average lifetime of scatternets that are formed with discoveryTO=5sec. This additional control avoids unnecessary scatternet updates, decreasing the power consumed during scatternet formation and increasing lifetime therefore.

The average lifetime is related to the number of total updates through the operation of the scatternet which is shown in Figures 5.4 and 5.6. From these graphs, it is seen that scatternet updates take place most frequently once an hour for large number of nodes.

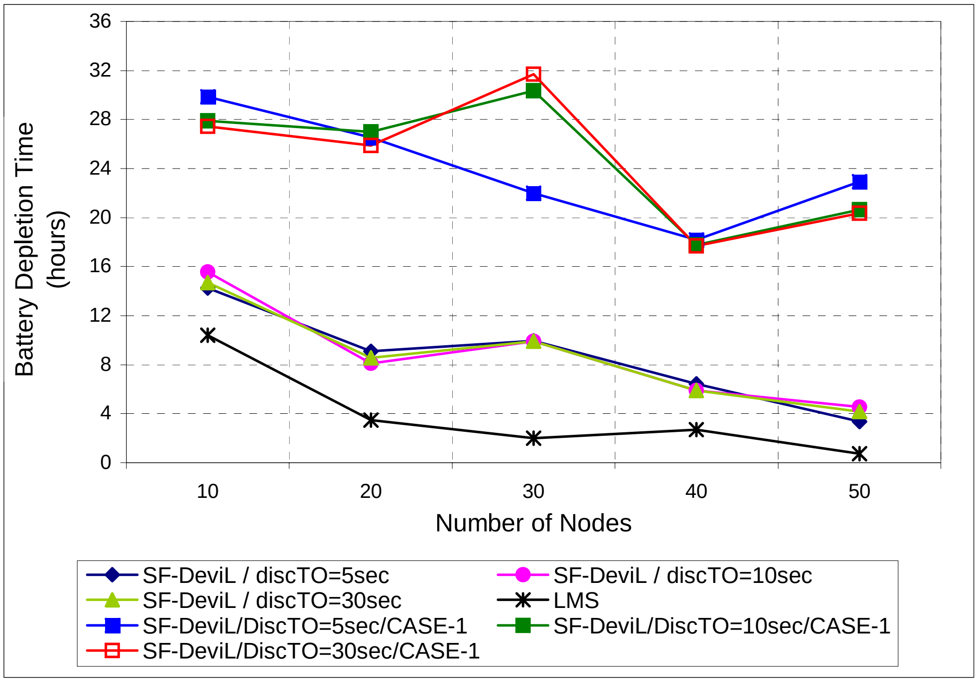


Figure 5.3: Time until the battery of first device depletes with scatternet update CASE-1

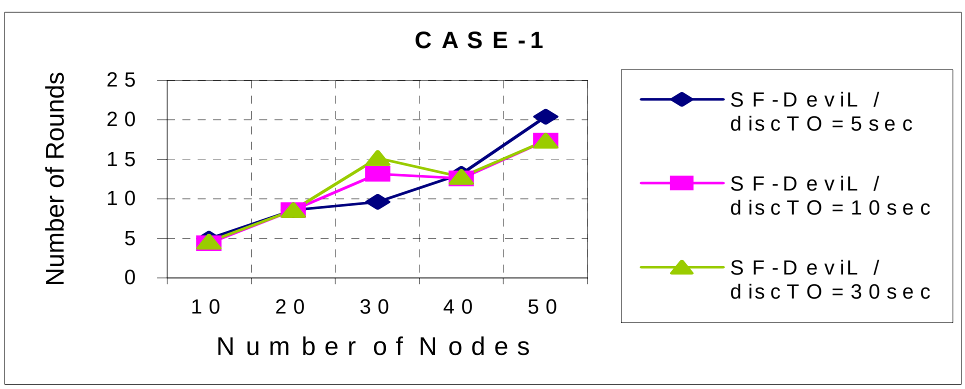


Figure 5.4: Number of rounds of scatternet updates for CASE-1

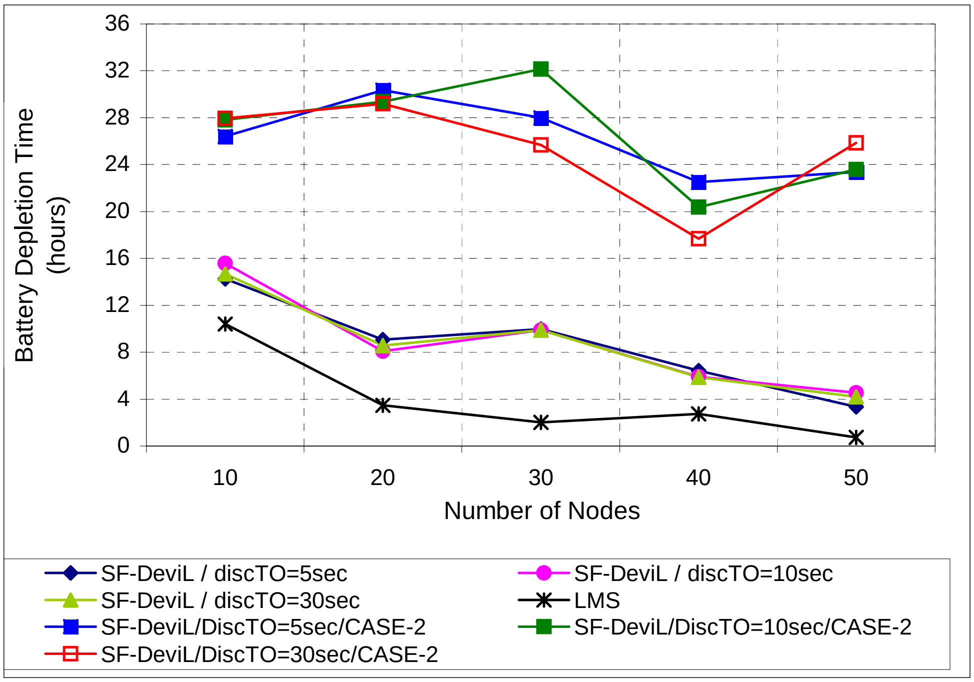


Figure 5.5: Time until the battery of first device depletes with scatternet update CASE-2

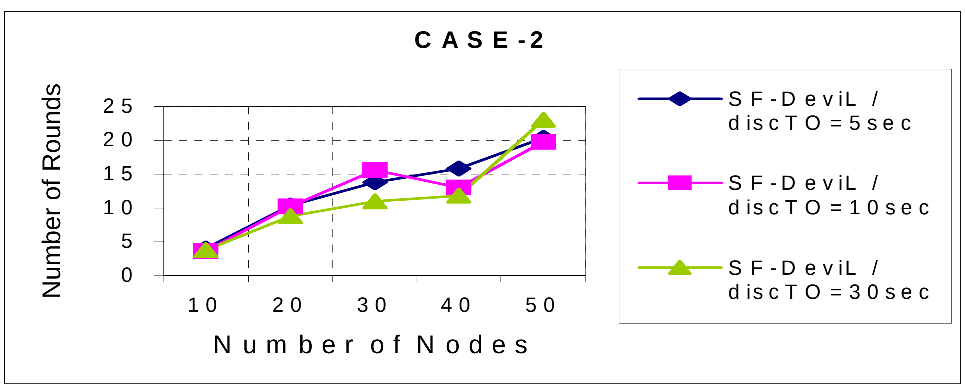


Figure 5.6: Number of rounds of scatternet updates for CASE-2

5.2.1.1.1 Average Update Time Per Round

The average time required for update of the scatternet per round is given in Figure 5.7. Since update is done through P/PS procedures, it increases linearly with increasing number of nodes.

The average total update time required for a 50 node case is equal to (number of total rounds) x (update time per round), which is about 23x1,5=34,5sec. 34,5 seconds is a short time compared to the average lifetime of a 50-node-scatternet, which is about 24 hours.

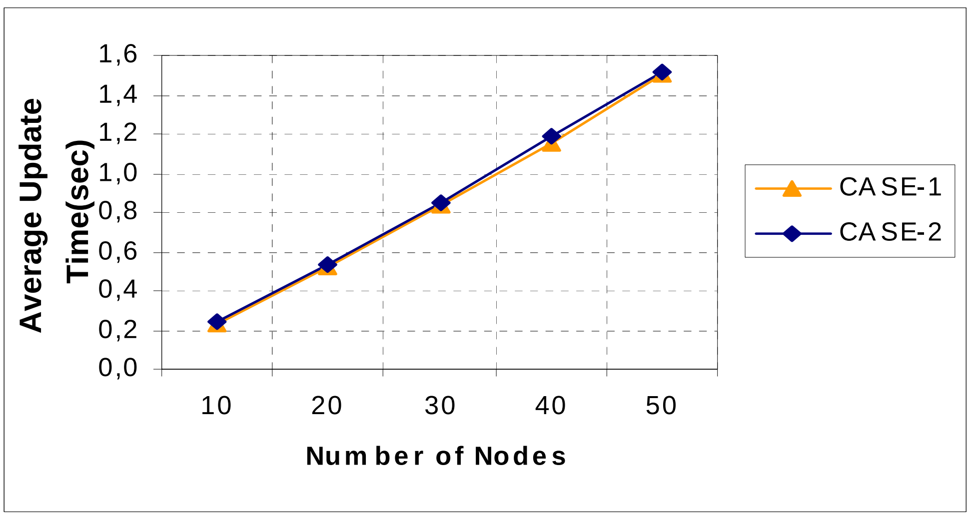


Figure 5.7: Average update time per round

5.2.2 Average Hop Number

Average number of hops between source-destination pairs as shown in Figure 5.8. As the number of nodes increases, owing to the tree topology, the average number of hops increases and not much difference exists between LMS and SF-DeviL scatternets.

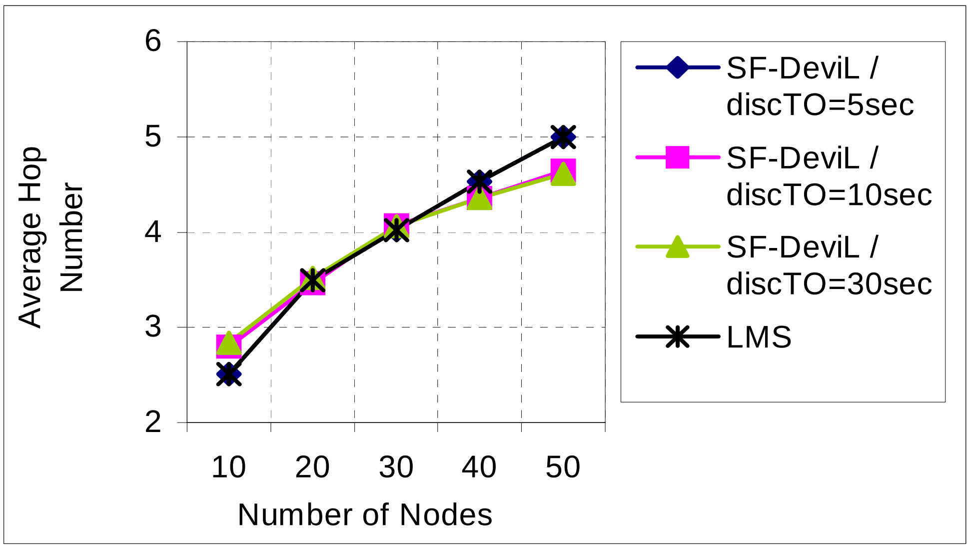


Figure 5.8: Average number of hops between source-destination pairs

5.2.3 Average Link Length

SF-DeviL forces each node to connect to the closest node with highest DG. For this reason, the average distance between connected nodes is smaller compared to LMS as shown in Figure 5.9. As the number of nodes increases, the nodal density increases resulting in shorter links. SF-DeviL scatternets formed by discoveryTO=5sec result in longer links, deviating from the objections of SF-DeviL algorithm. Shorter links result in less transmit powers and less interference for other wireless technologies such as IEEE 802.11b which also uses the ISM band.

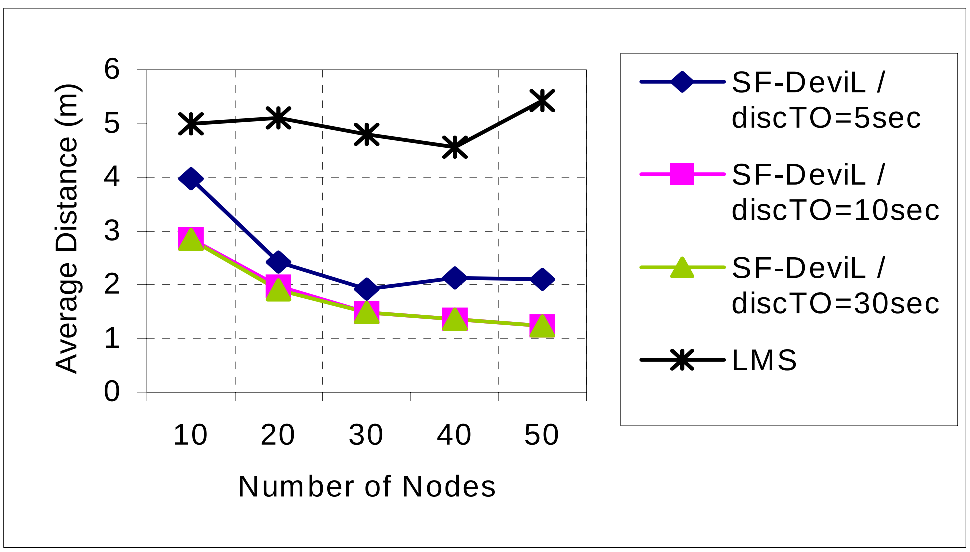


Figure 5.9: Average length of links in the scatternet

5.2.4 Piconet Number

The objective of LMS is to form scatternets with minimum number of piconets so as to reduce interference. For SF-DeviL, piconet number is not a parameter that is cared about. SF-DeviL aims to reduce interference by using power control and establishing links between closer nodes*.

As shown in Figure 5.10, the number of piconets of LMS is smaller than SF-DeviL and there is not a significant difference between different discoveryTO values of SF-DeviL.

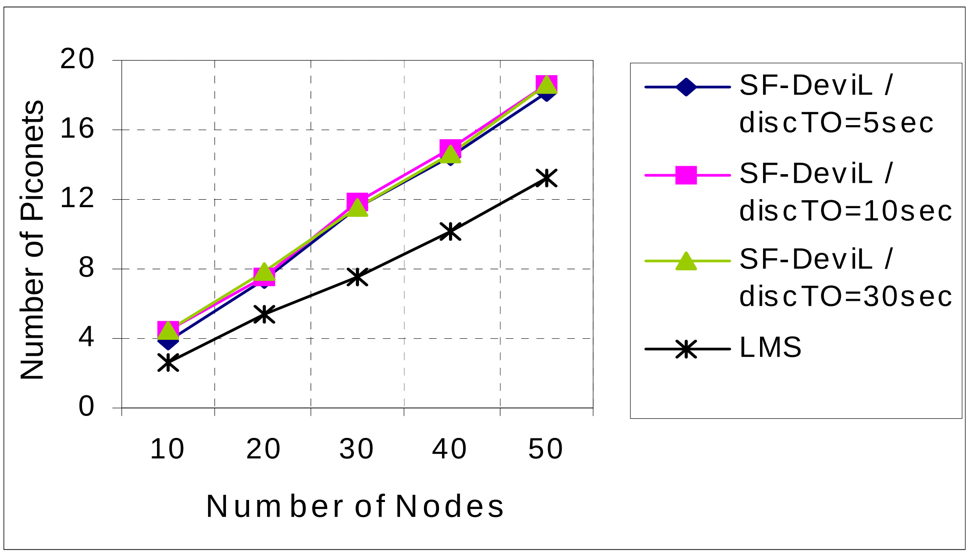


Figure 5.10: Number of piconets

* Interference of Bluetooth and Wi-Fi, that share the same ISM band, is a bigger problem than the interference of Bluetooth piconets, which both use FHSS. SF-DeviL is expected to work well for Bluetooth and Wi-Fi interference.

5.2.5 Network Diameter

Network diameter, defined as the maximum number of hops between two nodes, of SF-DeviL is slightly higher compared to the LMS algorithm for small number of nodes as shown in Figure 5.11.

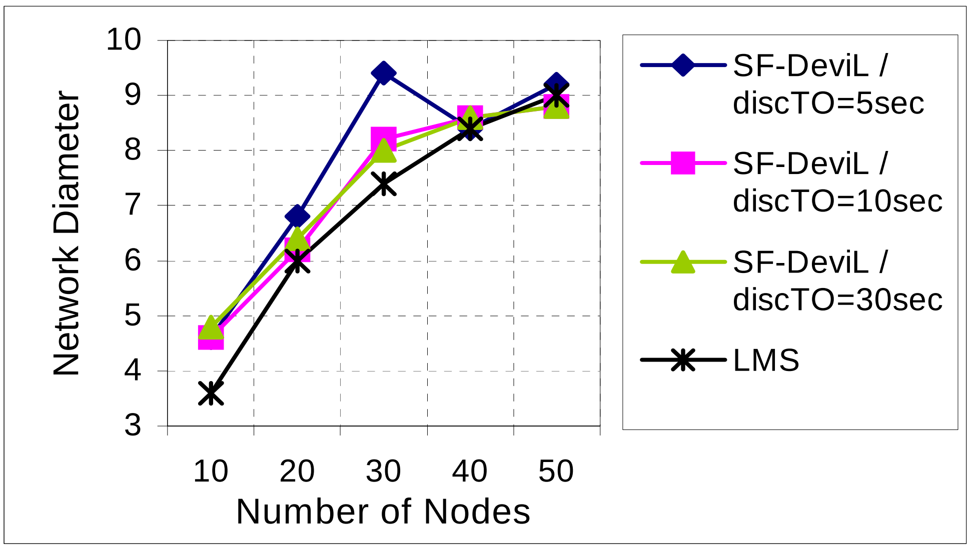


Figure 5.11: Network diameter

5.2.6 Scatternet Formation Delay

In Figure 5.12, connection delay for SF-DeviL is shown as a function of the network size for different timeout values. We observe that the formation of the scatternet takes longer than LMS. The connection delay for SF-DeviL increases with the network size. This is mainly due to the fact as the number of nodes increases, the size of neighbor_lists increases. Also nodes wait for discoveryTO before terminating neighbor discovery of procedure MAIN. While discovering more neighboring devices and choosing the best among them improves energy efficiency SF-DeviL, increasing discoveryTO increases connection delay. Therefore a reasonable timeout should be chosen.

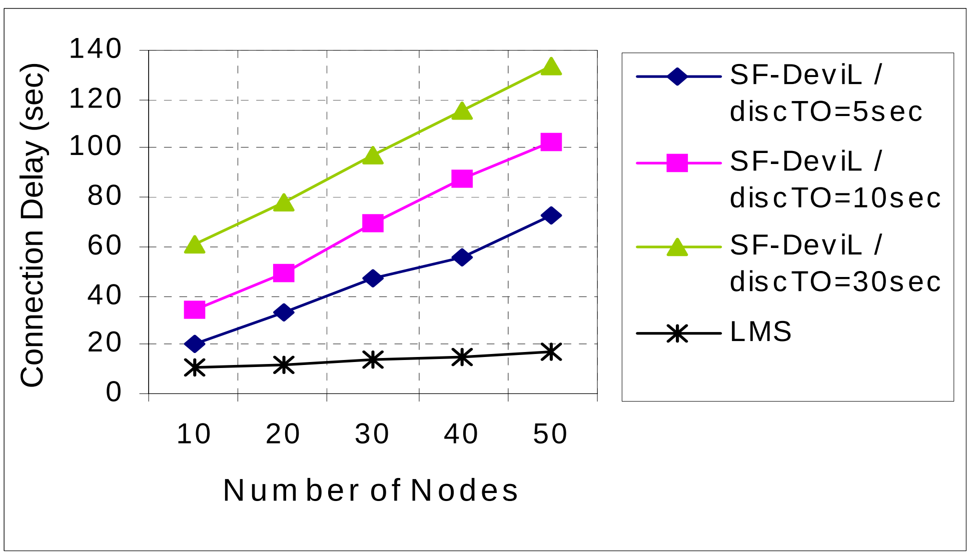


Figure 5.12: Scatternet formation delay

5.2.7 Percentage of Discovered Neighbors

Figure 5.13 shows the average percentage of neighbors discovered for the three timeout values for SF-DeviL. DiscoveryTO=5sec is just enough to discover about half of the neighbors, whereas with 10sec and 30sec timeouts, nearly all neighbors are discovered. A timeout of 30sec results in unnecessarily large connection delay and performs worse than 10sec timeout in terms of energy efficiency as seen in Figure 5.2. On the other hand, with a timeout of 5sec. network lifetime is smaller compared with discoveryTO=10sec, but the connection delay is significantly smaller. An appropriate value of the discoveryTO should be selected considering relative importance of network lifetime and connection delay.

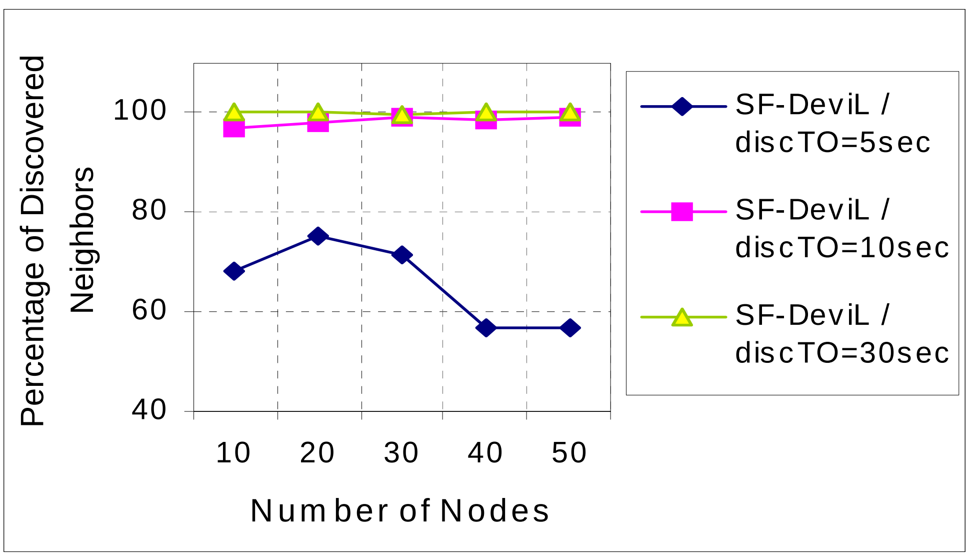


Figure 5.13: Average percentage of discovered neighbors in SF-DeviL for different timeouts

Chapter 6

CONCLUSIONS

6.1 Summary

SF-DeviL forms Bluetooth scatternets based on device classes and link parameters resulting in efficient use of energy. This is provided by using class of device information, measuring received signal strengths and taking care of battery levels of devices.

SF-DeviL operates in a distributed fashion and forms multihop scatternets. It can be adapted to current Bluetooth modules because it is compliant with the specifications.

SF-DeviL results in a spanning tree topology where powerful devices are chosen as root or bridges. The bridges are all M/S and two piconets are connected by at most one bridge node, which provides minimal overlap between piconets. Also since a bridge node participates in just two piconets, the bridge nodes do not become bottlenecks between multiple piconets.

Simulations prove that using class and link characteristics during scatternet formation, efficient power usage is achieved during operation. Updates of scatternet topology by changing battery levels, increases energy efficiency even more. SF-DeviL produces topologies with reasonable number of piconets, network diameters and connection delays.

The time complexity of the scatternet formation using SF-DeviL depends on the size of neighbor_list. Simulations have shown that a discoveryTO of 10sec. is enough to discover about all of the neighbors, which results in a reasonable connection delay. We also intend to incorporate recent work on reducing the connection establishment delay in Bluetooth, which will make SF-DeviL operate faster [21, 22].

6.2 Future Work

SF-DeviL is appropriate to work well in dynamic environments, where the rules are already explained in Section 4.3.2.2. Simulations in dynamic environments can be done a future work.

SF-DeviL scatternets have tree topologies. But since the optimum scatternet topology is application dependent [11], ways to form other topologies by SF-DeviL basics should also be investigated. SF-DeviL will be compliant to any application if it can be adapted to form different topologies upon user request.

We also intend to incorporate recent work on reducing the connection establishment delay in Bluetooth, which will make SF-DeviL operate faster [21, 22].

Table of Acronyms

AM_ADDR	Active member address
ACL	Asynchronous connectionless link
BD_ADDR	Bluetooth device address
BC	Battery capacity
BL	Battery level
CoD	Class of device
DAC	Device access code
DG	Device grade
DIAC	Dedicated inquiry access code
FHSS	Frequency hopping spread spectrum
I	Inquiry
IAC	Inquiry access code
IS	Inquiry scan
GFSK	Gaussian frequency shift keying
GIAC	General inquiry access code
P	Page
PS	Page scan
RSSG	Received signal strength grade
RSSI	Received signal strength indicator
SCO	Synchronous connection-oriented link
TDD	Time-division duplex
TGG	Traffic generation grade

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