Bluetooth Scatternet Formation in Wireless Mobile Ad Hoc Networks

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Abstract

Bluetooth Scatternet Formation in Wireless Mobile Ad Hoc Networks

Luding Jia

The problem of Bluetooth scatternet formation is: given *N* isolated wireless mobile Bluetooth devices, how to form a scatternet to satisfy a set of general guidelines and performance metrics? The scatternet formation protocol is an open issue in the Bluetooth specification [1]. The topology of a scatternet has a great effect on the performance of the network. There are many ways to construct a scatternet with a given set of *N* Bluetooth devices, but so far there are very few papers that discuss the issues related to scatternet formation.

This major report focuses on the problem of the scatternet formation in Bluetooth mobile ad hoc networks. We critically summarize the current research on scatternet formation and give the advantages and the disadvantages of each scatternet formation protocol. Then, we describe some general guidelines and performance metrics for scatternet formation. Finally, we propose three new topologies for Bluetooth scatternets called DRT, RFCM, and CMT, and compute various performance metrics for them. All three topologies have good scatternet performance.

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1 Introduction

Bluetooth is an emerging short range, robust, low complexity, low power, low cost, and local area wireless mobile ad hoc networking radio technology [1] [2] [3] that supports wireless connectivity among cell phones, headsets, PDAs, digital cameras, laptop computers, mice, and printers etc. Bluetooth was promoted in February 1998 by five promoters — Ericsson, Nokia, IBM, Toshiba and Intel. These companies formed a special interest group (SIG), which is supported now by thousands of Bluetooth SIG member companies. Bluetooth wireless technology is for voice and data communication, and is intended to replace interconnect cable, by sending data at 1 Mbps among various electronic digital devices via radio waves. 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 five slots. Bluetooth-enabled devices share 79 channels of 1 MHz bandwidth within the unlicensed 2.45 GHz Industrial-Scientific-Medical (ISM) band for wireless communication.

Each Bluetooth device as a node in network can perform the role of a *master* and/or a *slave* [1] [8] [15]. Two or more Bluetooth units sharing the same channel form a *piconet*. One Bluetooth unit acts as the master which selects a frequency hopping sequence for the piconet and controls traffic on the piconet, whereas the other units acts as slaves which are synchronized to the hopping sequence of the master. Thus, two Bluetooth-enabled devices can form a minimal piconet for communication, where one is the master and the other is the slave. One piconet consists of one master and up to K active slaves. According to Bluetooth specification [1], K is now 7. In addition, many more slaves can remain locked to the master in a so-called parked state. These *parked* slaves cannot be active on the channel, but remain synchronized to the master. Both for active slaves and for parked slaves, the channel access is controlled by the master. All packets are exchanged between a master and its slaves within a piconet. In a piconet, the channel is shared using a slotted time division duplex (TDD) protocol where a master uses a polling style protocol to allocate time-slots to slaves. There is no direct master-master or slave-slave communication. A device can be a slave in several piconets but be a master in only one piconet. It participates in the different piconets on a time-division multiplex basis.

According to [1], multiple piconets may cover the same area. Since each piconet has a different master, the piconets hop independently, each with their own channel hopping sequence and phase as determined by the respective master. In addition, the packets carried on the channels are preceded by different channel access codes as determined by the master device addresses. As more piconets are added, the probability of collisions increases; a graceful degradation of performance results as is common in frequency hopping spread spectrum systems (called Frequency Hopping Code-Division Multiple Access or FH-CDMA). With FH-CDMA technology, the carrier frequency at which the information-bearing signal (data signal) is transmitted is rapidly changed according to the code signal.

If multiple piconets cover the same area, a unit can participate in two or more overlaying piconets by applying time multiplexing. To participate on the proper channel, it should use the associated master device address and proper clock offset to obtain the correct phase. As mentioned before, a Bluetooth unit can act as a slave in several piconets, but as a master only in a single piconet. This is because two piconets with the same master are synchronized and use the same hopping sequence. A group of piconets in which connections exist between different piconets is called a *scatternet*.

A piconet is a basic communication unit in the scatternet. A subset of slave nodes may act as *bridges*. The bridge nodes are capable of timesharing between multiple piconets, receiving data from one piconet and forwarding it to another. The bridge node is a gateway for connecting two or more piconets to form a scatternet. The bridge node has two basic types: Master/Slave (M/S) or Slave/Slave (S/S). A M/S bridge node is a master in one piconet and a slave in the others, while a S/S bridge node is a slave in all piconets that it participates in. Since a node can only be a master in one piconet, no other type of bridge node is possible.

The *degree* of a node in a Bluetooth scatternet is the number of nodes it is connected to. A master node can connect to at most seven slaves, *i.e.*, the degree of the master nodes is at most seven. A non-bridge slave node (or unshared slave node or pure slave node or slave node for short when there is no confusion with the following bridge slave node) can connect to only one master, *i.e.*, the degree of the non-bridge slave nodes is equal to one. A bridge slave node (or shared slave node or bridge node for short) will connect to at least two piconets, *i.e.*, the degree of the bridge node is greater than or equal to 2. Two slaves cannot be connected directly.

In a scatternet, the total number of nodes or more precisely the total number of active Bluetooth nodes is denoted by N, the total number of piconets is denoted by P, the diameter of the scatternet is denoted by D which is the maximum distance between any pair of nodes in the network.

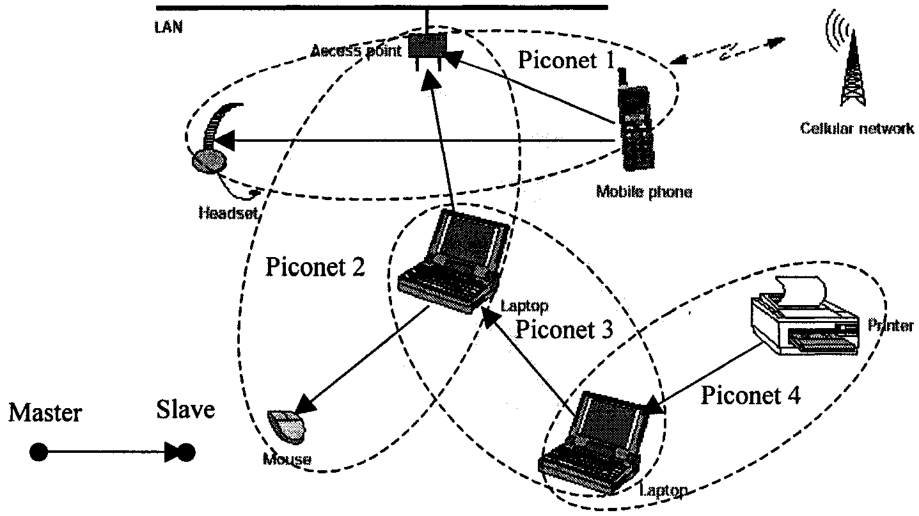

Figure 1.1 A scatternet of four piconets.

Figure 1.1 shows a scatternet formed from seven nodes ($N = 7$). Note that there are four piconets ($P = 4$), four master nodes ($M = 4$), three bridge nodes ($B = 3$), six links ($L = 6$), and two types of bridge nodes (Slave/Slave (S/S) and Master/Slave (M/S)). The diameter of the scatternet is five ($D = 5$). From Figure 1.1 we can easily see that in a scatternet, the number of piconets P is exactly equal to the number of master nodes M ($P = M$); the number of bridge nodes B is greater than or equal to the number of piconets P minus 1 ($B \geq P - 1$); and the number of links L is greater than or equal to the number of nodes N minus 1 ($L \geq N - 1$). These basic relationships in a scatternet will be discussed in detail in the following chapters.

There are two types of wireless mobile networks [26]. One is the infrastructure network with fixed and wired gateways. The base stations act like bridges. A mobile node that is in the network connects to and communicates with the nearest base station within its communication range. The other type of network is the infrastructureless network or the ad hoc network. Ad hoc networks have no fixed routers; all nodes can move arbitrarily and can be connected dynamically. All nodes can act as routers in the network. Multi-hop routing is used for forwarding packets beyond the communication range of the source's node. Many studies have concentrated on the routing protocols of ad hoc networks [26] [27]. These studies usually assume that any two in-range nodes can directly communicate with each other.

The Bluetooth ad hoc networks bring new challenges and constraints. A Bluetooth ad hoc network is a scatternet. In a Bluetooth ad hoc network, two in-range nodes may not communicate with each other directly if they are not in the same piconet or if they are in the same piconet but do not have a master-slave connection. In other words, only a master and a slave in the same piconet can directly communicate with each other. In the same piconet two slave nodes can communicate only through their master. Multiple channels are used for communication in a Bluetooth ad hoc network. Since multiple channels are used throughout the network, the topology of the Bluetooth ad hoc network (scatternet) is implicitly determined not only by distance relationship but also by master-slave connection, piconet specification, and scatternet formation protocol among the nodes.

The scatternet formation protocol is an open issue in the Bluetooth Specification [1]. However, as shown by Miklos *et al.* [6], Bhagwat *et al.* [8], Kalia *et al.* [10], Barriere *et al.* [23], and Zurbes [29] etc., the configuration of a scatternet has a great effect on the performance of the network. For example, the larger the diameter *D* of the scatternet, the larger is the delay of the scatternet, and the smaller is the capacity of the scatternet. The more nodes a bridge node connects to, the more the bridging overhead, and the worse the bottleneck at the bridge node.

The problem of Bluetooth scatternet formation is: given *N* isolated wireless mobile Bluetooth devices, how to form a scatternet to satisfy a set of general guidelines and performance metrics? Such a scatternet formation protocol as an explicit topology construction protocol must be asynchronous and distributed, and nodes should not be assumed to have any information about each other. There are many ways to construct a scatternet with a given set of *N* Bluetooth devices. But so far there are very few papers that discuss the issues related to scatternet formation.

This major report will study scatternet formation in wireless mobile Bluetooth ad hoc networks. It is organized in the following way:

- Chapter 2 summarizes the current research on scatternet formation and gives the advantages and the disadvantages of each scatternet formation protocol.
- Chapter 3 describes some general guidelines for scatternet formation and performance metrics for scatternets and divides the metrics into two categories: static metrics and dynamic metrics.
- Chapter 4 proposes three new topologies for Bluetooth scatternets called DRT, RFCM, and CMT and evaluates their performance metrics.
- Chapter 5 gives the conclusions and lists the possible future work.

2 Current Research on Scatternet Formation

The problem of scatternet formation in Bluetooth networks has only recently been proposed, and there are only a few research papers studying the questions. The results are far from definite. In this chapter, we describe some of the suggested protocols and try to give the advantages and disadvantages for each protocol. We will focus on the scatternet performance metrics, scatternet formation and maintenance, the scatternet topologies, and the scatternet routing methods, etc. which are related to each other.

Kalia *et al.* [10] give three basic scatternet structures: Single Piconet Model (SPM), Two-Level hierarchy of Piconets (TLP), and Shared Slave Piconets (SSP). The SPM is the simplest scatternet structure that contains only one piconet. In the piconet, there is one master, up to seven slaves in active mode, and up to 256 slaves in park mode. In park mode a slave cannot transmit or receive data in the piconet. The parked slave has to listen to periodic master transmissions to keep synchronized. Parking/Unparking a slave has an overhead on the system performance due to the slot wastage. There is no wireless inter-piconet communication within SPM. A slave is parked or unparked with a timestamp. The parked slave with the oldest timestamp such as PS_{255} in Figure 2.1 is periodically unparked and an active slave with oldest timestamp such as S_6 is parked. Each slave remains unparked (active) for the same time interval. But each slave remains parked for a different time interval depending on how many parked slaves there are at that time. For a large number of slaves, the time they remain parked can be significant. This kind of scatternet has low throughput and high delays. Also the maximum number of nodes is limited.

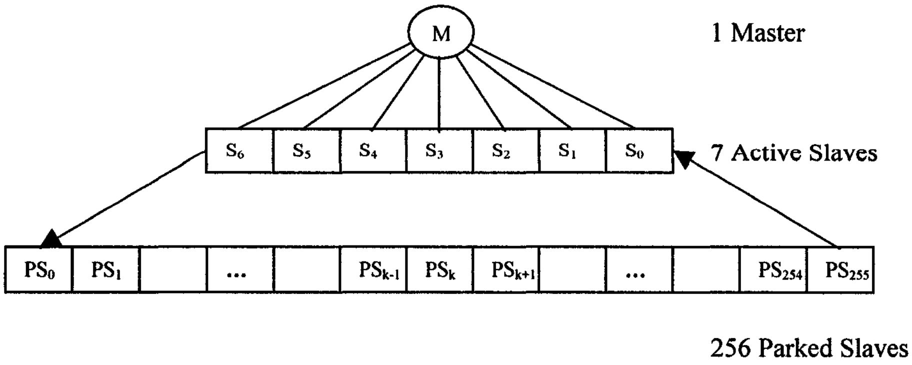

Figure 2.1 Single Piconet Model (SPM).

The two-level hierarchy of piconets (TLP) also proposed in [10] is composed of one root piconet and up to seven leaf piconets organized in a two-level hierarchy like a tree topology as shown in Figure 2.2. The traffic going through the piconet is buffered at the master. A leaf piconet must suspend communication when its master node enters active mode in the root piconet. This is the problem when the bridge node to connect two piconets has a M/S configuration, *i.e.* master in one piconet and slave in another. The suspension of communication in the leaf piconet can be avoided by making a slave in the leaf piconet a temporary master.

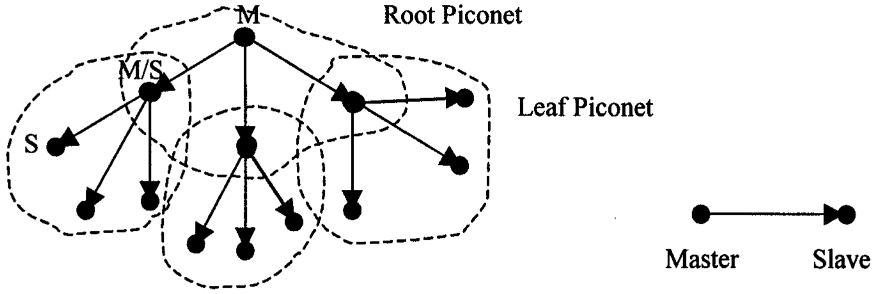

Figure 2.2 Two Level hierarchy of Piconets (TLP).

The maximum number of nodes N in a TLP configuration is relatively small ($N \leq 57$) and the total number of piconets P is less or equal to 8. If N is 57, P is 8. The scatternet will have a smaller value of the slope of piconet-node curve (P-N curve) than others (see below). This means that it has less number of piconets and better performance. In the TLP, the traffic between any two piconets will go through the master of the root piconet. Therefore, the root piconet will become a bottleneck due to centralized design.

The third scatternet topology in [10] is shared slave piconets (SSP). This is a fully connected topology because there is a direct connection between every pair of piconets in the scatternet through a shared slave. The slave as bridge node is active in both piconets alternately. The bridge node here has an S/S configuration, *i.e.* it is a slave in both piconets that it participates in. Inter-piconet data traffic is routed through the common slave.

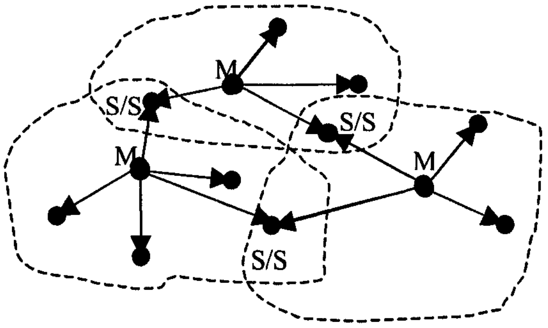

Figure 2.3 Shared Slave Piconets (SSP).

This is a decentralized design with better load balancing and is more robust. In general according to [10], there may be only one slave that is a shared bridge among all piconets in vicinity, and act as a router among the piconets. Therefore, there is heavy load on the bridge, which will become the bottleneck. The diameter of an SSP network is at most four, which is optimal. The cost of direct connections between every pair of devices is high and many connections may be vastly underutilized, however. If every pair of piconets shares a slave, the total number of nodes in the scatternet is limited to $N \leq 36$. This is discussed in detail in Salonidis *et al.* [11].

From the simulation results of [10], the system throughput in an SPM network is less than that in TLP which is less than that in SSP (SPM < TLP < SSP). The average system delay is SPM greater than TLP and TLP greater than SSP (SPM > TLP > SSP). Thus the SSP has the smallest and the best system delay and largest and best throughput.

Salonidis *et al.* [11] introduce a scatternet formation algorithm called Bluetooth Topology Construction Protocol (BTCP). BTCP is based on a leader election process and has three phases. First, a leader as coordinator is elected with complete knowledge (count, identities, and clocks) of all devices (nodes) that are in radio transmission range of each other. Second, the leader, which knows the address and clock information of all nodes, will tell them how a scatternet should be formed and determine the scatternet topology. Finally, in the third phase, the actual connections are established. In BTCP, the scatternet topology is determined by a single device called the leader and therefore, BTCP has more flexibility in constructing the scatternet. One limitation of the algorithm is that it assumes that all the nodes are in communication range of each other.

Salonidis *et al.* propose and justify the following default properties that the resulting network should satisfy:

1. Because each portable device may have limited processing capability, a bridge node should connect only two piconets, *i.e.* the bridge node degree is two. (Bridge degree constraint). This relieves a bridge node from being an overloaded crossroad of multiply originated data transfers.

2. The resulting scatternet should consist of the minimum number of piconets. The smaller the number of piconets in the scatternet, the easier for network controlling.
3. The resulting scatternet should be fully connected. Every master will be connected to all other masters through bridge nodes. Scatternets are expected to change over time. A fully connected scatternet in its initial state provides higher robustness against topology changes. Scatternet routing becomes simple because every node in the scatternet can reach every other node through a bridge node or a master node.
4. Two piconets share only one bridge (Piconet overlap constraint). If two masters later wish to share another bridge between them they can do so by means of a bridge negotiation protocol.

The Bluetooth scatternet with BTCP is a fully connected topology and is presented as a fully connected non-planar graph in [11]. It uses only slaves as bridges with degree 2. This protocol works only for up to 36 devices ($1 \le N \le 36$, N is the total number of nodes), for the conference scenario where all nodes are turned on at nearly the same time, and for all nodes within proximity of each other. These are the constraints of the protocol.

The number of piconets is given by

$$P = \left\lceil \frac{17 - \sqrt{289 - 8N}}{2} \right\rceil, \quad 1 \le N \le 36$$

where N is the number of nodes. From the above relation, the default scheme works for a number of nodes less than or equal to 36 due to the desired properties 2 - 4 described above. According to [11], a larger number of nodes (> 36) may lead to a not fully connected scatternet. Then the scatternet becomes a not fully connected non-planar graph, but this structure is not described in [11].

For any N $(1 \le N \le 36)$ in the BTCP algorithm, the distance between any pair of nodes is less or equal to 4. Therefore, the network diameter $D \le 4$. This is an optimal value for the diameter and means less delay and better performance for the scatternet with $N = 36$ and $P = 8$, which is shown in Figure 2.4. This is the same as SSP in Figure 2.3.

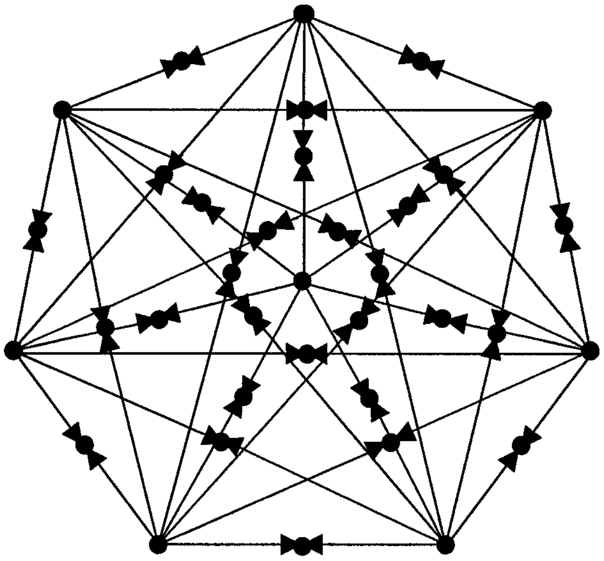

Figure 2.4 BTCP constructing a fully connected mesh topology with $N = 36$.

In [11], there is still much work that remains to be done. For example, the scatternet formation here is a static method and does not deal with dynamic issues. After network connection, a separate topology maintenance and optimization protocol needs to run, in order to take care of mobility and/or nodes entering and leaving the network and to make sure that the scatternet is reformed accordingly. The protocol also needs to be extended for the case when not all nodes are within communication range of each other. In this case, after completion of the election process, the coordinator will learn about all participating nodes but not all of them will actually be within its range. It is possible that some nodes will never get connected. It seems as though BTCP cannot be easily extended for the case when not all nodes are in range.

Ramachandran *et al.* [14] propose two new distributed clustering algorithms for scatternet formation in wireless ad hoc networks. The first is a 2-stage distributed $O(N)$ randomized algorithm for an N node complete network, which always finds the minimum number of star-shaped clusters of maximum size. The second is a completely deterministic $O(N)$ time distributed algorithm in which clusterheads (masters) are elected autonomously by the nodes. Each algorithm elects a "super-master" which is a master that has received responses from all other clusters, and has information about all the nodes in the network. The authors do not give a specific scatternet topology construction algorithm. They only deal with electing a super-master. The elected super-master can then run any centralized algorithm to form a scatternet of desired topology. This is similar to the protocol in [11] which depends on a single device to design the scatternet topology and then notify the other nodes.

Both algorithms have time complexity $\Omega(N/k)$ [16], where N is the number of nodes, and k is the maximum number of slaves in a scatternet. Both algorithms require all nodes to be in range of each other. The authors do not handle the situation of nodes dynamically joining and leaving. They assume the conference scenario in which a set of nodes is powered on at the same time and start executing these algorithms immediately in order to form a connected set of clusters. These topology construction algorithms should ensure the following.

- The nodes should be organized into star-shaped clusters (piconets), each of which has a clusterhead or Master. In each cluster, a Master is at the center of the star, and the rest are all Slaves.
- The maximum number of Slaves per cluster is S.
- The size of the clusters should be at their maximum.
- The exchange of roles between a Master and a Slave is expensive, and should be avoided.
- The transfer of nodes from one cluster to another after connection is established is also expensive, and should be avoided.
- At the end of the algorithm, each node knows whether it is a Master or a Slave. If it is a Slave, it knows the Master of the cluster it belongs to.
- The network should be connected, and there should be no orphan nodes.
- On termination, a single node should have complete information about all the clusters.

The simulation results show that the randomized algorithm performs better with respect to both cluster and network formation times.

Law *et al.* [15] [16] present an algorithm that has only one phase (or dividing into two phases similar to the three phases of Salonidis *et al.* [11], one is leader selection, the other is the actual connection establishment): the scatternet is formed once a leader is elected. The number of piconets is as small as possible. Nodes can only dynamically join the scatternet. The protocol assumes that all devices are in the communication range of one another. Two performance measures and three quality measures for a scatternet formation protocol are proposed:

- Time complexity: amount of time to form a scatternet. A scatternet must be formed as fast as possible to minimize the delay experienced by the users.
- Message complexity: number of messages sent between the devices. This is important because Bluetooth devices usually operate with limited power. By reducing the number of messages sent, power consumption is conserved.
- Number of piconets: a measurement of the efficiency of a scatternet. Since all piconets share the same set of 79 channels, there will be more collisions when there are more piconets. As shown in [27], the burst failure rate increases with the number of piconets.
- Maximum degree of the devices: the maximum number of piconets that any device belongs to. Since the piconets communicate through shared slaves, if a slave belongs to many piconets, then this slave could become the bottleneck of inter-piconet communications. A shared slave has to be time multiplexed between the piconets that it belongs to.
- Network diameter: maximum number of hops between any pair of devices. This provides an estimation of the maximum routing delay of the scatternet.

In the algorithm, initially, a set of isolated but in-range devices are given. During the execution of the algorithm, the devices are partitioned into components. A component is a set of interconnected devices. A component can be a single device, a piconet, or a scatternet. There is one leader in each component. All leaders execute procedures to enable the nodes to find each other and to form the scatternet according to different cases.

The algorithm forms a scatternet with $m - 1$ devices of degree 2 and $n - m + 1$ devices of degree 1, where n is the number of devices and m is the number of piconets.

The algorithm achieves $O(log\ n)$ time complexity and $O(n)$ message complexity. The algorithm shows that, 1) in the formed scatternet, any device is a member of at most two piconets, in other word, the degree of any bridge slave node (shared devices) is exactly two, with which the network bottlenecks are avoided; and 2) the number of piconets is close to minimal as $m \le \lfloor (n-2)/(k-1) \rfloor + 1$, here k is the number of slaves in a piconet. There are two types of bridge nodes M/S and S/S in the scatternet described below. Thus, the scatternet will meet the M/S bridge problem. The algorithm results in a scatternet with a tree topology.

The current protocol already handles the events of devices joining the scatternet. Additional work is required to deal with the case of devices leaving or failing. They give an outline of a possible solution:

- If a master fails (or leaves the network), then a new master can be elected from the slaves. If the failed master is shared (*i.e.* this master is M/S type bridge node), then the new master should become a leader and merge with the rest of the scatternet.
- If a shared slave fails (*i.e.* this slave is S/S type bridge node), its master should become a leader again and then it will be connected to the rest of the scatternet.
- Nothing needs to be done when an unshared slave fails, unless it is the only unshared slave of an active leader.
- In general, if a leader without unshared slave fails, then this leader has to disconnect from its shared slaves. Other masters connected to this leader through the shared

slaves should now become leaders again. This will allow the protocol to proceed as usual. The authors claim that expensive reorganization should be a rare event.

This may work because all nodes are in communication range. Comparing with BTCP in [11], BTCP can construct the scatternet in a much more flexible manner because the coordinator has information about all the nodes in the scatternet.

Tan *et al.* [17] present an efficient topology formation algorithm, called the TSF (Tree Scatternet Formation) protocol, which assigns master/slave roles to nodes while connecting them in a tree topology. This simplifies both the routing of messages and the scheduling of communication events. Routing is simplified because there is no routing loop in the scatternet and there exists a unique path between any two nodes. Nodes can be assigned unique addresses based upon their position in the tree. The algorithm is decentralized and self-healing, in that nodes can dynamically join and leave the scatternet at any time without causing long disruptions in connectivity. The algorithm allows nodes to arrive and leave arbitrarily, incrementally building the topology. There is no requirement for all nodes being within radio range of each other. There is also no restriction on the number of nodes in the scatternet. The algorithm achieves the minimum number of average piconets per bridge node. Every bridge node connects to exactly two piconets. The type of bridge node used is M/S which may potentially suspend the communication of all its slaves when the bridge node acts as a slave in its parent piconet. They present simulation results that show that TSF has low tree formation latency and generates an efficient topology for forwarding packets. This protocol works not only for the conference scenario but also beyond it and it allows nodes dynamically joining or leaving at any time. Two problems with their protocol are that the root node can be overloaded and a node leaving can break the network connection.

There are two modes during a scatternet formation. In the first mode, most (or all) nodes join *en masse*, such as in a scheduled meeting with several participants equipped with Bluetooth devices. This is also called a conference scenario like in [11]. In the second mode, nodes join and leave a scatternet at any time. The goal in [17] is to efficiently construct topologies for both these modes of operation.

TSF has the following properties that meet the requirements of the above two operating environments.

1. Connectivity: TSF constantly attempts to converge to a steady-state in which all nodes can reach each other.
2. Healing: TSF handles nodes joining and leaving incrementally, avoiding loops and healing network partitions.
3. Communication efficiency. TSF produces topologies where the average node-node latency is small (logarithmic in the number of nodes, avoiding long chains).

Figure 2.5 shows the scatternet topology produced by TSF for a 50-nodes scenario. The 50 nodes (N = 50) in the scatternet are divided into two parts, 25 nodes are root nodes (masters) and 25 nodes are non-root nodes (slaves). All root nodes except root 6 or root 26 are also bridge nodes with M/S type. Therefore, there are 24 bridge nodes connecting 25 piconets in the scatternet (P = 25).

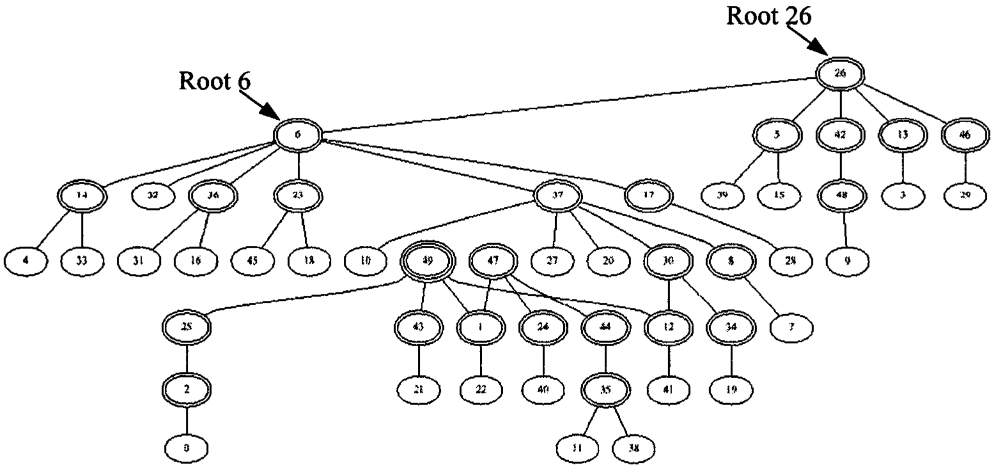

Figure 2.5 A 50-node scatternet created with TSF.

The communication latency between two nodes in the scatternet is governed largely by three factors in [17]: i) hop count, ii) intra-piconet scheduling delay and iii) inter-piconet bridging delay. The values of each component vary based on the scheduling and routing policies. There is no generally accepted scheduling scheme for scatternets. Moreover, since there are relatively few deployed Bluetooth networks, finding representative and realistic traffic patterns for performance evaluation is difficult, if not impossible.

Zaruba *et al.* [19] give two algorithms to form a tree topology scatternet named Bluetree with M/S type bridge nodes and the maximum number of slaves assigned to a piconet by the scatternet construction algorithm is 5. All nodes need not be in range of each other. The degree of bridge node is ≤ 2 in the Blueroot Grown Bluetrees algorithm and ≤ 3 in the Distributed Bluetrees algorithm. They consider the network with low node mobility.

Blueroot Grown Bluetrees algorithm is based on a designated node as “blue-root”, that initiates the construction of a “Bluetree”. The number of roles assigned to one node is limited to two, a master, a slave, S/S type bridge, and M/S type bridge. For example, in Figure 2.6, there are $N = 21$ nodes, one blueroot, 9 slave nodes, 11 bridge nodes with M/S type, and $P = 12$ in the scatternet. Distributed Bluetrees algorithm speeds up the scatternet formation by selecting more than one root for tree formation, and then merging the sub-trees generated by each root. For example, in Figure 2.7, there are 21 nodes in total, 5 sub-trees, and $P = 15$. The degree of the nodes is less than or equal to 3.

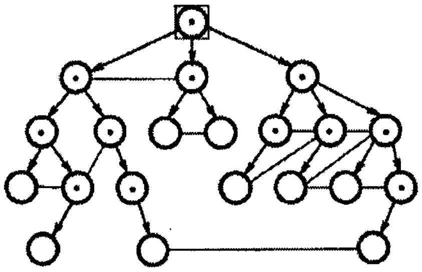

Figure 2.6 A rooted Bluetree (the squared node is the blueroot).

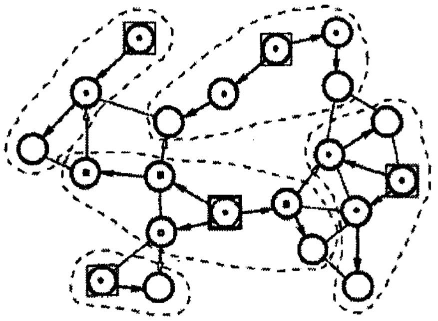

Figure 2.7 Combined distributed Bluetrees.

Both algorithms yield tree topologies, allow M/S type bridges, and do not require all nodes to be in range of each other. The parent nodes will be bottlenecks in the scatternet, specially in blueroot node which is a single node and will be the root of the bluetree.

Sun *et al.* [20] present algorithms to embed a b-tree (binary search tree) into a scatternet which enables easy routing. It requires only fixed sized message header and no routing table at each node. It scales well to large sized scatternets and deals with devices dynamically joining or leaving. The scatternet topology is tree-based (called as Blue-tree) with multiple level M/S type bridge nodes in degree of two. The concept of Blue-tree is the extension of the b-tree. This will create the same suspension problem as TLP in [10]. It discusses also eliminating Master/Slave bridges and replacing with Slave/Slave bridges, but this is not efficient because the change is after a scatternet is constructed. This protocol works only for all nodes within radio transmission range of each other and for the conference scenario, as in [11]. Finally, the Blue-tree pruning procedure is time and resource consuming and causes a big overhead.

Figure 2.8 shows an example of how the algorithm in [20] deals with addition and deletion of nodes. Node 25 joins a Blue-tree and node 21 leaves the Blue-tree. When node 21 is leaving, node 35 discovers node 19 and 24.

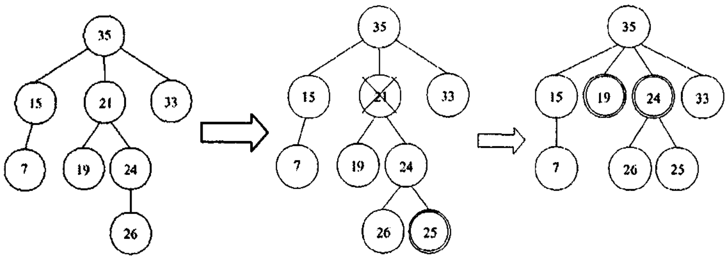

Figure 2.8 A sample Blue-tree with adding and deleting nodes in the Blue-tree [20].

Figure 2.9 shows an example of how to merge two independent Blue-trees. Just like adding an isolated node, node 20 is as a child of node 35. Then, according to the protocol, prune the tree to get the final Blue-tree as shown on the right-hand side of Figure 2.10.

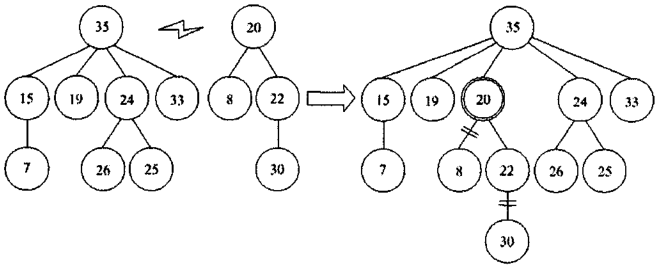

Figure 2.9 Merging Two Independent Blue-trees [20].

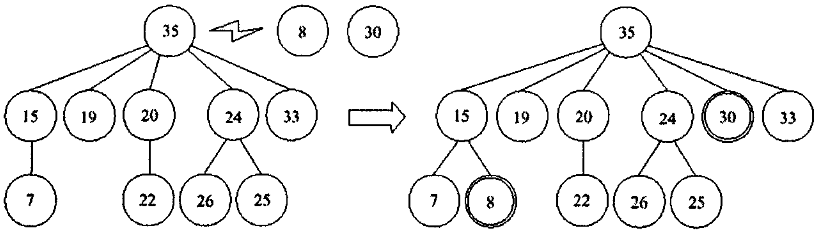

Figure 2.10 Pruning Blue-tree and the Final Blue-tree.

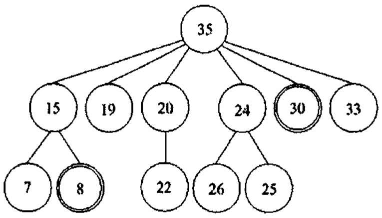

Figure 2.11 The final Blue-tree.

Wang *et al.* [21] give a protocol called Bluenet that creates a scatternet like a more connected mesh topology. It is a more balanced network structure but with more links.

This scatternet topology is also with multiple level M/S or S/S bridges with degree greater than or equal to 2. In Figure 2.12 the bridge node 11 is a M/S type bridge acting as a master in one piconet and a slave in six piconets. The bridge nodes have the suspension drawback and will easily become a bottleneck in the scatternet.

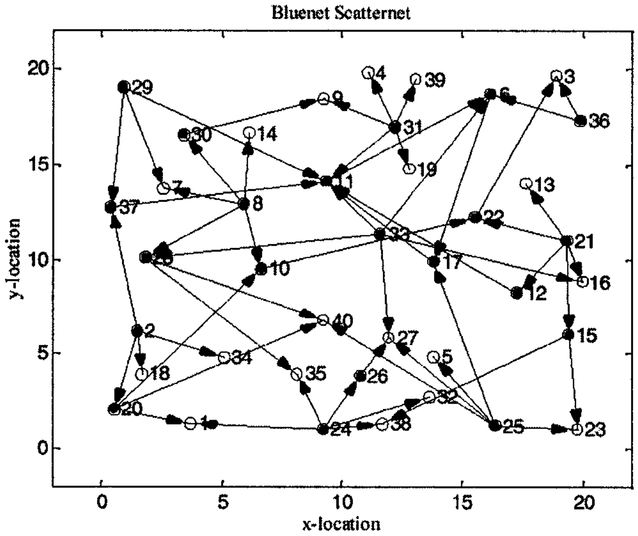

Figure 2.12 A Sample Bluenet Scatternet.

In Figure 2.12, nodes 25, 8, 21, 24, 31, and 33 have maximal 5 slaves that are with the constraint of max number of slaves in a piconet being 5. There are 40 nodes and 21 piconets with 21 masters in the scatternet. This means more piconets than that in the following Bluetree Scatternet shown in Figure 2.13 for the same configuration of nodes. All bridge nodes are M/S type with degree 2. Node 21 has maximal 5 slaves that are nodes 3, 6, 19, 31, and 36 with the constraint of max number of slaves in a piconet being 5. The nodes 12, 16 and 17 are the same as node 21 with 5 slaves. There are 40 nodes and 12 piconets with 12 masters in the scatternet. This means less piconets than that in

Bluenet Scatternet due to using the tree topology. The simulations of both samples are based on the conference scenario. All nodes are not required in radio range of each other.

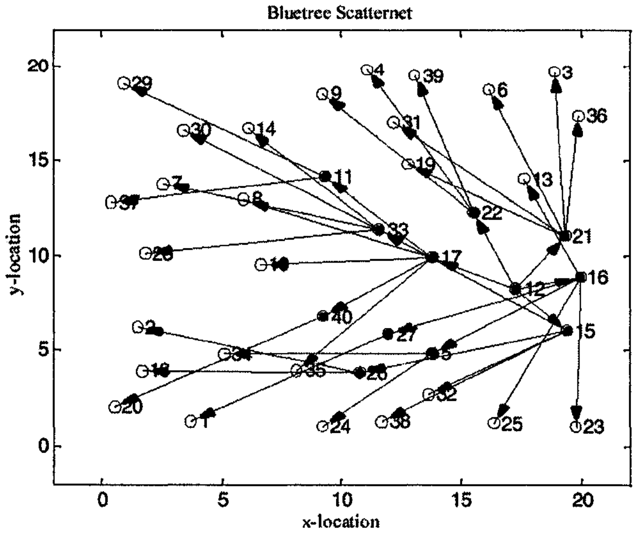

Figure 2.13 A Sample Bluetree Scatternet.

Foo *et al.* [22] present a protocol called BlueRing which creates a Bluetooth scatternet like a ring topology. A BlueRing has benefits in terms of reliability, ease of packet routing and scheduling. Compared to the MIT-BSFA algorithm given by Law *et al.* [15] described earlier, which also gives a tree scatternet, a BlueRing has superior traffic performance (network capacity, throughput and delay per flow) for small network sizes of up to 40 nodes. This paper also proposes two distributed algorithms to form a BlueRing, named NODE_ID and HEAD_SEEKSCAN.

The properties of the BlueRing are:

- All nodes are arranged in a ring configuration.
- Each node acts as a Master-Slave (M/S) type bridge.

- Each node belongs to two piconets and has exactly two links in total. Each piconet has exactly two nodes.
- There exist two fully disjoint paths between any two nodes in the ring.

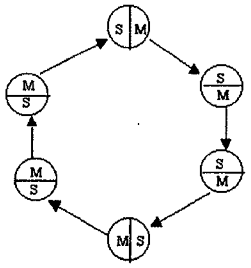

Figure 2.14 A Sample of BlueRing Scatternet with 6 Nodes.

The benefits of BlueRings are:

- Improved reliability - Two paths between any two nodes.
- Simplified routing - No routing protocol or control message required.
- Minimized scatternet scheduling overheads - Only need to manage two links and two piconets per node.

The number of piconets and diameter as functions of the number of nodes for the BlueRing and the MIT-BSFA tree scatternets [15] are shown in Figures 2.15 and 2.16.

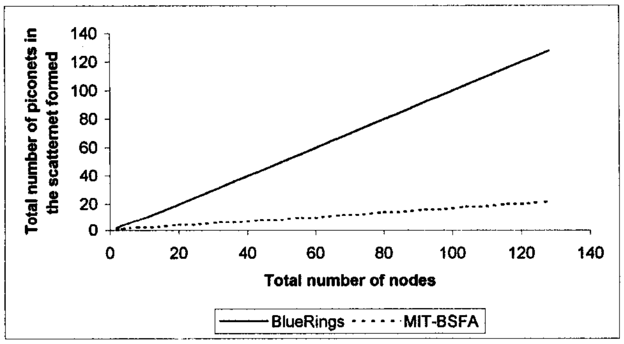

Figure 2.15 Compare the $P = f(N)$ of the BlueRing and a Tree Scatternet MIT-BSFA.

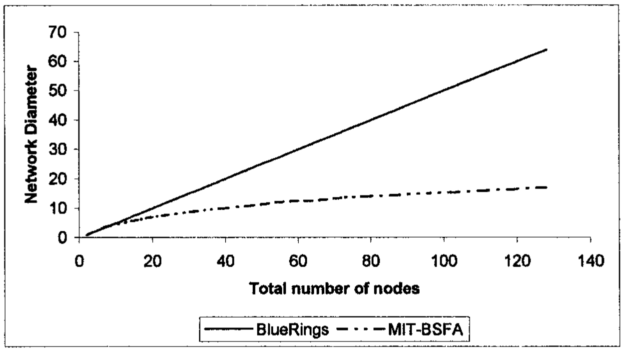

Figure 2.16 Compare the $D = g(N)$ of the BlueRing and a Tree Scatternet MIT-BSFA.

We can easily see that the total number of the piconets in the scatternet will be $O(N)$ as $P = N$ and the diameter of the scatternet will be also $O(N)$ as $D = N/2$. Both are worse than the tree topology. Therefore, potentially the scatternets using BlueRing topology will have larger number of piconets and larger network diameter than those using tree topology.

Barriere *et al* [23] present an efficient distributed algorithm for Bluetooth scatternet formation. It is supposed that all nodes are within transmission range of each other. The resulting scatternet is scalable and the algorithm is dynamic in the sense that nodes can join and leave the scatternet at their convenience. The algorithm reacts to a join or leave request with $O(\log^2 n \log^2 \log n)$ time in local computation, where n is the number of nodes in the scatternet. The message complexity of these operations is $O(\log^4 n \log^4 \log n)$ bits. Any join or leave involves only a limited number of rearrangements of the connections. These rearrangements are local to very few nodes. Bridge nodes are slaves in all piconets that they participate in. The degree of the scatternet can be fixed arbitrarily to any d equal to one plus the power of a prime. The topology of the scatternet is derived from a projective plane. The diameter of the scatternet is polylogarithmic in the size of the network, and the m-connectivity of the scatternet, which is defined as the smallest number of connections whose removal separates two masters, is high.

It gives also a simple routing protocol adapted to the specific scatternet topology returned by the formation algorithm. This protocol does not require complicated path-discovery methods, but is based on a simple virtual labeling of the devices participating in the scatternet. Given the label of the current node and the label of the destination node, the routing protocol returns the output port in $O(\log^2 n \log^2 \log n)$ time.

In [23], five performance metrics are given to ensure good performance of the resulting scatternet.

1. Small number of piconets
2. Small maximum degree of bridge nodes
3. Small diameter
4. High connectivity of masters
5. Dynamic scalability

An example of an incomplete scatternet of 128 nodes denoted as *SCT*(128,8,1) is shown in Figure 2.17.

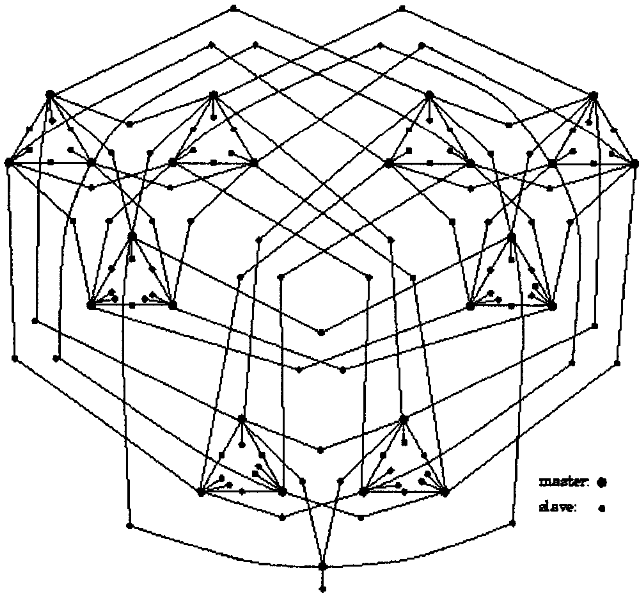

Figure 2.17 *SCT*(128,8,1)

From the above discussion, all the previous work is summarized into Table 2.1 according to the criteria of topology, whether nodes joining and leaving are dealt with, degree and type of bridges, diameter of network, whether all nodes are required to be in transmission range, the maximum number of nodes allowed, and the number of piconets.

Comparing all related work on scatternet formation with each other, there is no perfect protocol that can be the best in all performance metrics. Some tradeoff must be made among the various performance metrics.

Paper	**Kalia** *et al* [10]	**Salonidis** *et al* [11]	**Ramachandran** *et al* [14]	**Law** *et al* [15]	**Tan** *et al* [17]	**Zaruba** *et al* [19]	**Sun** *et al* [20]	**Wang** *et al* [21]	**Foo** *et al* [22]	**Barriere** *et al* [23]
Topology	tree/fully connected mesh	fully connected mesh	any, as chosen by super-master	tree	tree	tree	tree	highly connected	ring	based on projective plane
Maximum Number of Nodes	8 (SPM) 57 (TLP) 21 (SSP)	36	arbitrary	arbitrary	arbitrary	arbitrary	arbitrary	arbitrary	arbitrary	arbitrary
Number of piconets	1 (SPM) 8 (TLP) 3 (SSP)	8	no bound given	$\left\lfloor \frac{n-2}{6} \right\rfloor + 1$	no bound given	no bound given	no bound given	no bound given	no bound given	$\frac{n}{4.5}$
Deal with nodes Joining/Leaving	no	no	no	yes, join	yes, both	no	yes, both	no	no	yes, both
Bridge Node Type	M/S (TLP) S/S (SSP)	S/S	Supermaster chooses type	M/S	M/S	M/S, S/S M/S/S	M/S	M/S S/S	M/S	S/S
Bridge Node Degree	≥ 2	2	Supermaster chooses degree	2	2	2 (BGB) ≤ 3 (DB)	2	≥ 2	2	2
Network Diameter	2 (SPM) 4 (TLP) 4 (SSP)	≤ 4	no bound given	no bound given	no bound given	no bound given	no bound given	no bound given	no bound given	$\log^2 n \log^2 \log n$
Nodes required in radio range of each other	yes	yes	yes	yes	no	no	yes	no	yes	yes

Table 2.1 Summary and comparison of related works (n is the number of nodes in the scatternet).

3 General Guidelines and Performance Metrics

In this chapter, we outline some general guidelines for scatternet formation algorithms and describe metrics that may be used to evaluate their performance.

3.1 General Guidelines for Scatternet Formation

The following general guidelines should be followed by algorithms for the scatternet formation.

1. *Use nodes that are resource-rich or not very mobile to play the central roles in a scatternet.* One way to do this is to define the available resources of each kind of nodes as an identity and then use the identity of each node during the construction of the scatternet.
2. *The number of nodes N in a scatternet should not be limited to a fixed number.* In a piconet, the number of nodes N is at least one.
3. *The number of piconets P in a scatternet should be as few as possible.* Let K denote the maximum possible number of active slaves in a piconet. According to the current Bluetooth specification, $K = 7$. Let $S_{\max}$ be the maximum number of slaves assigned to a piconet by the scatternet construction algorithm. Then $S_{\max} \le K$. All packets are exchanged between a master and its slaves within a piconet. There is no direct master-master or slave-slave communication. A device can be a slave in several piconets but be a master in only one piconet. One piconet is one basic communication

unit in the scatternet. The more the piconets in a scatternet, the more the co-channel interference the scatternet has, the higher the rate of packet collisions will be. For all algorithms, in a scatternet of N devices, if $N = 0$ then $P = 0$ which is the minimal value of P, if $N = 1$ then $P = 1$, if $N = 2$ then $P = 1$. In general, $\lceil N/(S_{\max}+1)\rceil \leq P \leq N$. The number of piconets depend on not only N, but also the scatternet topology, the number of links (bridges) between the pairs of piconets, and the maximal number of slaves ($S_{\max}$) in a piconet etc. For example, a scatternet with a tree topology tends to have fewer piconets. The number of piconets is equal to the number of masters in a scatternet.

4. *The type of bridge nodes should be Slave/Slave (S/S) with degree of two.* There are two basic types of bridge nodes. One is Master/Slave (M/S) in which the bridge node is master in one piconet and slave in another piconet. The other is Slave/Slave (S/S) in which the bridge node is slave in both piconets. The S/S bridge node is preferred over M/S bridge node. The M/S bridge nodes must keep many connections and can easily become a communication bottleneck in the scatternet. While switching between the master and slave roles may be feasible, it is very wasteful because of the communication suspension. When a M/S bridge node is a slave in its parent piconet, all slaves in its own piconet in which it is master will be suspended until it comes back as master or selects another slave node as a temporary master. This suspension makes a large data traffic delay in a scatternet, especially in a tree topology, where if one piconet is suspended, it will block all piconets in the sub-tree to communicate with the other parts of the scatternet.

5. *It may be a good idea to not fully fill piconets.* During the initial scatternet formation, leaving room for more slaves in piconets avoids master node overload and also allows for faster reaction to network mobility. Both these improve the dynamic performance of a scatternet. S_{max} should therefore be less than K, where S_{max} is the maximal number of slaves in each piconet during building the initial network topology and K is the theoretically maximal number of slaves in each piconet, according to current Bluetooth specification. In [19] and [21], $S_{max} = 5$ slaves is chosen and the built scatternet has best dynamic performance on the average. This corresponds to filling a piconet with 70% of the maximum possible number of slaves K.

   $S_{max} = 5$ may make sense especially when all nodes are not necessarily in transmission range of each other. Otherwise, if all nodes are in range of each other, $S_{max} = 7$ can be chosen. When a new node joins the scatternet, because all nodes are in range and know each other very well, the new node can be put either in any existing piconet with less than 7 slaves or in a new piconet when all existing piconets in the scatternet are full. It should be noted that not fully filling a piconet will potentially create more piconets, which goes against minimizing the number of piconets, and degrades the performance of the scatternet.

6. *When it is possible, the percentage of the traffic of intra-piconets versus inter-piconets should be considered.* Ideally, the topology of the scatternet should be such that there is more intra-piconet traffic than inter-piconet traffic. This is to avoid overload or bottleneck at the bridge nodes. It means also that the piconets in a scatternet should have higher cohesion and lower coupling.

7. *All nodes should be able to easily and dynamically join and leave the scatternet as discussed in* [17] [20] [23]. Network connection establishment should be performed in a totally distributed fashion. This means that each device starts operating asynchronously on its own and it initially does not have any knowledge about the identities or number of nodes in the area.
8. *A scatternet formation protocol should consider the conference-scenario of an ad hoc network establishment.* In this scenario, we suppose that there are many users in a room within transmission range of each other that wish to form an ad hoc network using their Bluetooth enabled devices. Each user presses a "start" button and waits for the device to show on the screen a "network connection established" message after a short period of time. After this message appears, the user will be able to exchange information with any other user in the room.
9. *A scatternet formation protocol should consider the scenario when all nodes are not in radio transmission range of each other.* The algorithms in [11], [15], [20], and [22] require all nodes in radio transmission range of each other. The algorithms in [17], [19], and [21] do not need all nodes to be in range of each other.
10. *The protocol must guarantee a connected scatternet, when the visibility graph of the nodes is connected.* There must exist at least one link between any node and the rest of the scatternet.
11. *The network set up delay should be minimized so that it is tolerable by the end user.* The connections should be done as soon as possible.

12. *The scatternet should be reliable and robust.* A connected scatternet should be difficult or impossible to disconnect. The scatternet should deal with any node joining or leaving and ensure the network connection with the same performance.
13. *Maximize the scatternet security.* It should be difficult for an unauthorized user to get into the scatternet and access the information of the others.

3.2 Scatternet Performance Metrics

There are several different but related metrics for evaluating the performance of a scatternet after it has been formed according to [6] [7] [8] [9] [15] [21]. These performance metrics can be divided into two classes: static metrics and dynamic metrics.

The static performance metrics are quality measures of scatternets such as in [9], [11], and [15] and relate only to the network topology. They are determined by the scatternet formation protocol when the scatternet is being formed. In general, they have an impact on the dynamic performance of the network, but they can be measured statically. The dynamic performance metrics are based on time and space. They are measured by the dynamic evaluation of the scatternet performance after the scatternet has been formed. They may also relate to the dynamic properties of the scatternet formation protocol itself. For example, in Wang *et al.* [21], the average shortest path (ASP) is a static metric and in Law *et al.* [15], the time complexity and the message complexity are dynamic metrics. Some static metrics influence dynamic metrics. For example, Miklos *et al.* [6] shows clear trends in how the number of established links can affect throughput of a Bluetooth scatternet.

In the following two sections, the static and dynamic performance metrics for evaluating the scatternet performance are defined and described in detail.

3.2.1 Static Performance Metrics

The static performance metrics are quality measures of scatternets that relate only to the network topology. There are many static performance metrics described below.

1. Piconet to node curve of a scatternet denoted as *P-N* curve: This is for measuring and comparing the number of piconets for the different total number of Bluetooth nodes, according to different algorithms. We would like to express the number of piconets created by a scatternet formation algorithm as a function of the number of nodes in the scatternet. To do this, we first empirically obtain several data points given by pairs (p_i, n_i) where p_i is the number of piconets in a scatternet with n_i nodes. Then we try to obtain an approximation of the number of piconets as a polynomial function $f(x)$ by trying to minimize the error using standard techniques. For completeness, we describe the method below.

   Let

$$f(x) = a_0 + a_1 x + a_2 x^2 + \cdots\cdots + a_n x^n$$

   and suppose we have m data points

$$(x_1, y_1),\ (x_2, y_2),\ \ldots\ldots,\ (x_m, y_m)$$

   where x_i is the number of nodes and y_i is the corresponding number of piconets, we can estimate the function $f(x)$ as follows. Let the difference d_i between y_i and the curve $f(x)$ at x_i be the error

$$d_i = y_i - f(x_i) = y_i - (a_0 + a_1 x_i + a_2 x_i^2 + \cdots\cdots + a_n x_i^n)$$

Let c be the square error

$$c = \sum_{i=1}^{m} d_i^{\,2} = \sum_{i=1}^{m} [y_i - f(x_i)]^2$$

To make fit error minimal, select a_0, a_1, ……, a_n to make c minimal, so

$$\frac{\partial c}{\partial a_i} = \frac{\partial}{\partial a_i}\left(\sum_{i=1}^{m} [y_i - f(x_i)]^2\right) = 0$$

When $n = 1$, we get the linear fit case,

$$f(x) = a_0 + a_1 x$$

where

$$a_0 = \frac{\sum_{i=1}^{m} y_i \sum_{i=1}^{m} x_i^2 - \sum_{i=1}^{m} x_i y_i \sum_{i=1}^{m} x_i}{m\sum_{i=1}^{m} x_i^2 - \left(\sum_{i=1}^{m} x_i\right)^2} \text{ and } a_1 = \frac{m\sum_{i=1}^{m} x_i y_i - \sum_{i=1}^{m} x_i \sum_{i=1}^{m} y_i}{m\sum_{i=1}^{m} x_i^2 - \left(\sum_{i=1}^{m} x_i\right)^2}$$

For the *P-N* curve, since $N = 0$, $P = 0$ in all algorithms, $a_0 = 0$ and $f(x) = a_1 x$, therefore

$$\frac{\partial c}{\partial a_1} = \frac{d}{da_1}\left(\sum_{i=1}^{m} [y_i - a_1 x_i]^2\right) = -2\sum_{i=1}^{m} [y_i - a_1 x_i] x_i = 0$$

$$a_1 = \frac{\sum_{i=1}^{m} x_i y_i}{\sum_{i=1}^{m} x_i^2}$$

We can estimate P to be

$$P = \lceil a_1 N \rceil$$

where x_i is the number of nodes, y_i is the number of piconets at x_i, and m is the number of (x_i, y_i) data pairs. Given N, the smaller a_1 is, the fewer the number of piconets P in a scatternet, the fewer the bridge nodes in the scatternet, the smaller the diameter D of the scatternet, the less the capacity of the scatternet.

The P-N curve or the P-N trendline with the linear fit can be also called the P-N line. Similarly, we can get the fit cases when $n > 1$, such as $n = 2$ and $n = 3$ for more accurate fit and of course more calculations. Higher value of a_1 means that more piconets will be in the scatternet when N is increased, and the worse the performance of the scatternet. The algorithm should result in smaller value of slope a_1. Since $P = N$ is the maximal value of P, we have $a_1 \leq 1$.

2. Diameter of the network: The diameter D of the scatternet is the maximum distance over all pairs of nodes. The diameter D in a piconet is two (for one master and more than one slave). Like P-N curve, we can get D-N curve in the same way as $D = \lceil a_1 N \rceil$.

   The diameter of the scatternet has a direct impact on the message delivery. Given N, the smaller a_1 is, the smaller the diameter D, the smaller the scatternet delay, the more the capacity of the scatternet. The algorithm should result in a smaller value of slope a_1. Since in one scatternet, when $N = 1$, $D = 0$, when $N = 2$, $D = 1$, therefore, $D = N - 1$ is the maximal value of D, $a_1 < 1$.

3. Maximum degree of bridge nodes: The degree of each bridge node is greater than or equal to 2 and less than or equal to max_bridge_degree. The higher the degree of the bridge nodes, the more piconets the bridge nodes belong to, and the more master or slave roles the bridge nodes play in different piconets. Consequently the more

difficult it is to find an efficient scheduling. Bridge nodes with smaller degree will simplify the scheduling strategy for good performance and reduce the bridging overhead.

4. Connectivity of masters: For any pair of master nodes (x,y), the number of edge-disjoint paths from x to y in the network must be large [23]. Let λ denote the m-connectivity of a scatternet, as defined the smallest number of connections whose removal separates two masters. Then $\lambda \leq K$. A high value of λ allows the traffic to be balanced among the different parts of the network, and limits contention between messages. This leads to a robust scatternet topology. The more connections there are between two piconets through bridge nodes, the more robust and the more reliable the scatternet will be, and the more maintenance overhead is in the scatternet. According to the industrial system reliability practices, double connection between each pair of piconets using two bridge nodes increases reliability.
5. Average Shortest Path (ASP): The ASP metric is defined as the average shortest path-length among all 2-node pairs in a Bluetooth network. Obviously ASP relates only to the network topology. ASP has impact on the scatternet delay and capacity.
6. The number of Bluetooth links L: According to [6], the number of established Bluetooth links is one of two characteristics that have a major impact on system performance. There is a link number where the throughput is maximized. Increasing the number of links allows more traffic in the scatternet and also may increase capacity of the network, but it increases the overhead of a node participating in more piconets. The number of links L is related to the number of piconets P.

3.2.2 Dynamic Performance Metrics

In this section, we describe several dynamic performance metrics for scatternets:

1. Bridging overhead: Because a Bluetooth node (device) can transmit or receive in only one piconet at a time, bridge nodes must switch between piconets on a time division basis. A Bluetooth node needs to synchronize its hopping frequency from one piconet to another, perform the necessary signaling, and take some time for switching. The time and battery power required for these tasks are called the bridging overhead. According to [6], the amount of bridging overhead can have a major impact on system performance.
2. Dynamic scalability: The process of a new node joining or leaving a scatternet should be relatively simple and the diameter or the *m*-connectivity of a scatternet should not degrade with repeated join and leave operations.
3. Time complexity: The amount of time to form a scatternet in the conference scenario can be called the time complexity. A scatternet must be formed as fast as possible to minimize the delay experienced by the users.
4. Message complexity: The number of messages sent between the devices to construct the scatternet in the conference scenario can be called the message complexity. This is important because Bluetooth devices usually operate with limited power. By reducing the number of messages sent, power consumption is conserved.
5. Maximum Traffic Flow (MTF): The maximum number of messages that can be delivered at the same time in a scatternet is called the maximum trafic flow. This is also a measure of the maximum network throughput.

6. Average scatternet delay or average system delay: The average time delay for the message delivery in a scatternet should be as small as possible.
7. Capacity of the scatternet: As defined in [30], the capacity of the scatternet is the total network throughput and depends on the average number of nodes in a piconet and the average path length. A smaller number of nodes in a piconet implies a larger number of piconets P and increased capacity in the scatternet. Similarly a lower average path length implies more capacity because longer chains waste the capacity at all intermediate masters. A larger number of piconets generally results in longer average path length.

3.3 Application of General Guidelines and Performance Metrics

Many general guidelines and performance metrics for scatternet formation have been proposed in this chapter. How to use them in scatternet formation is an important question. There is no scatternet formation protocol that can satisfy all static and dynamic performance metrics. Indeed, some of the desirable characteristics contradict each other. For example, constant degree of nodes cannot be achieved simultaneously with constant diameter. There are many tradeoffs among the various performance metrics to form the best possible scatternet. In the next chapter, we propose some scatternet topologies and we evaluate the scatternet performance according to the different tradeoffs among the proposed performance metrics.

4 Topology of Bluetooth Scatternets

From the preceding discussions, we can see that the topology of a scatternet constitutes an important part of the infrastructure of the network and plays a very important role for both static and dynamic performance metrics. A scatternet with good topology will have good static performance and furthermore will have good dynamic performance. In this chapter, the topology and related characteristics for scatternet formation will be discussed in detail.

Because a Bluetooth scatternet is a Bluetooth ad hoc network which is a special case of a general ad hoc network, all or partial topologies and related characteristics for scatternet formation in this chapter may be used to form a general ad hoc network such as in the case of clustering algorithms for wireless ad hoc networks in [14].

There are four basic network configurations, namely, bus, ring, star, and fully connected mesh as shown in Figure 4.1. Figure 4.1a and b are bus and ring configurations in which all nodes are connected to a single circuit. Such configurations can be used in small local area networks (LANs) or personal area networks (PANs) for data communication by transmitting messages one at a time. The bus configuration requires $n-1$ links and the ring requires n links. In Figure 4.1c a circuit (link) is formed from each node to a central hub node where a switching algorithm connects pairs of nodes as required. This results in the star configuration which requires only $n-1$ links. Figure 4.1d shows the fully connected mesh configuration in which a link is provided between each pair of nodes. If there are n nodes, this requires $n(n-1)/2$ links, which is $O(n^2)$.

Bluetooth scatternets can employ the topologies of the basic configurations in Figure 4.1a, b, c, and d, while respecting the restrictions on master/slave connections, and kepping the degree of bridge nodes low.

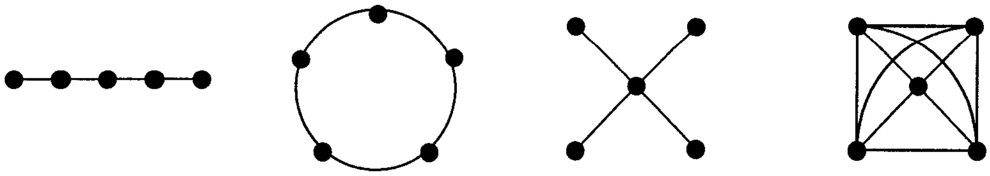
(a) Bus (b) Ring (c) Star (d) Mesh

Figure 4.1 Basic network configurations.

In the following section, we assume bridge nodes are of S/S type and degree two. Clearly a scatternet with a bus topology can be shown in Figure 4.2. The diameter of such a scatternet increases linearly with the number of nodes.

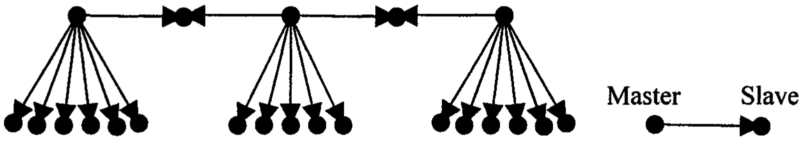

Figure 4.2 Scatternet with bus topology ($K = 7$).

A scatternet with a ring topology can be easily obtained by adding one bridge node to the bus topology as shown in Figure 4.3. The diameter of the scatternet is similar to the bus and increases linearly with the number of nodes. A ring topology is more reliable than the bus because there are two paths between any pair of masters. It is straightforward to extend that for any number of nodes.

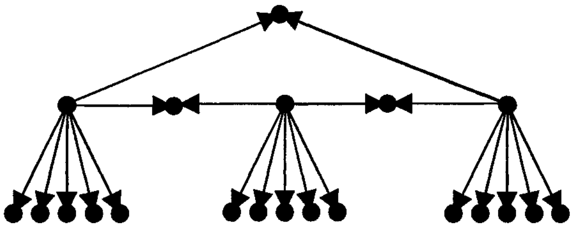

Figure 4.3 Scatternet with ring topology ($K = 7$).

Multiple stars form tree structures. Trees represent a hierarchical arrangement of nodes. The top level of the hierarchy consists of a single node which may form a bottleneck for communications or a fully connected subset of all nodes which may be less likely to form a bottleneck. A hierarchical topology ensures that there is a fixed number of links and nodes that can be involved in the interconnection of any two nodes in the network. Therefore, the tree and the mesh topologies can be combined together to form a mesh-tree or tree-mesh combined topology with better performance.

The basic tree topology of a scatternet as shown in Figure 4.4 is based on the K-ary tree The advantages of the basic tree topology are fewer piconets, no routing loop, simplicity, constant degree of bridge nodes, and low diameter ($O(\log N)$). The problems of the tree topologies are the bottleneck on root piconet, lower connectivity, lower reliability when bridge nodes fail or leave, and reduced network capacity (for full-sized piconets).

The basic fully connected mesh topology for a scatternet is shown in Figure 2.4. It has the optimal diameter and several connections between any two nodes in the scatternet. Therefore, it is more connected and more reliable. It can also deal with nodes leaving the scatternet very well.

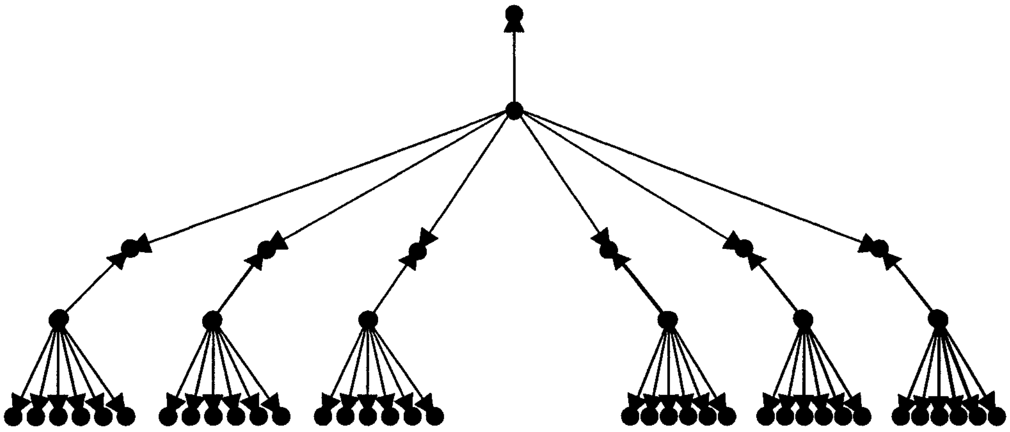

Figure 4.4 Scatternet with tree topology ($K = 7$).

In the following section, we propose three new scatternet topologies: the double redundant tree (DRT), recursively fully connected mesh (RFCM), and combined mesh-tree (CMT) topologies. We discuss the number of piconets and diameter of these toplogies in detail. These new topologies are based on the following assumptions:

- The total number of Bluetooth nodes N is not limited.
- All nodes are in communication range of each other.
- All master nodes have at most K slaves, *i.e.* degree is K.
- All bridge nodes are of S/S type and their degree is 2.
- All nodes are turned on at the same time to form the Bluetooth scatternet (the conference scenario).

4.1 Double Redundant Tree Topology of Scatternets

4.1.1 Description of DRT Topology

In this section, we describe a new topology for Bluetooth scatternets, called the double redundant tree (DRT) topology and shown in Figure 4.5.

There is one master node and K slave nodes in each piconet in Figure 4.5. If K is odd, we make $K - 1$ slave nodes as bridge nodes to connect to the other $\frac{K-1}{2}$ piconets in the scatternet. One slave node is reserved for the replacement of one node leaving the scatternet. Except for the master at the root, two slave nodes are used to connect to one parent piconet and the remaining ($K - 3$) slave nodes are used to connect to $\frac{K-3}{2}$ child piconets. If K is even, we make $K - 2$ slave nodes as bridge nodes to connect to $\frac{K-2}{2}$ other piconets in the scatternet. Two slave nodes are reserved for the replacement of two nodes leaving the scatternet. Except for the master at the root, two slave nodes are used to connect to one parent piconet and the remaining ($K - 4$) slave nodes are used to connect to $\frac{K-4}{2}$ child piconets.

We suppose K is odd in Figure 4.5 (in current Bluetooth specification $K = 2^3 - 1 = 7$). There are two bridge nodes of S/S type acting as double links between every parent-child pair of piconets. These two paths can play equal roles in the scatternet. Packets can be sent and received between every parent-child pair of piconets through either of the two paths. If one bridge node fails the other bridge node can still forward the packets to ensure that the scatternet is still connected.

In the DRT topology, there exist two kinds of redundancies to make the final scatternet more reliable and to minimize changes due to nodes failures or nodes leaving.

One is the redundant bridge with which the scatternet is more robust against failure in one of the two bridges. The other is the reserved slave node in each piconet which can be used as a replacement of a master node in case of a master failure or used as a replacement of any bridge node in case of a bridge failure. Therefore, this topology is more reliable, robust, and connected.

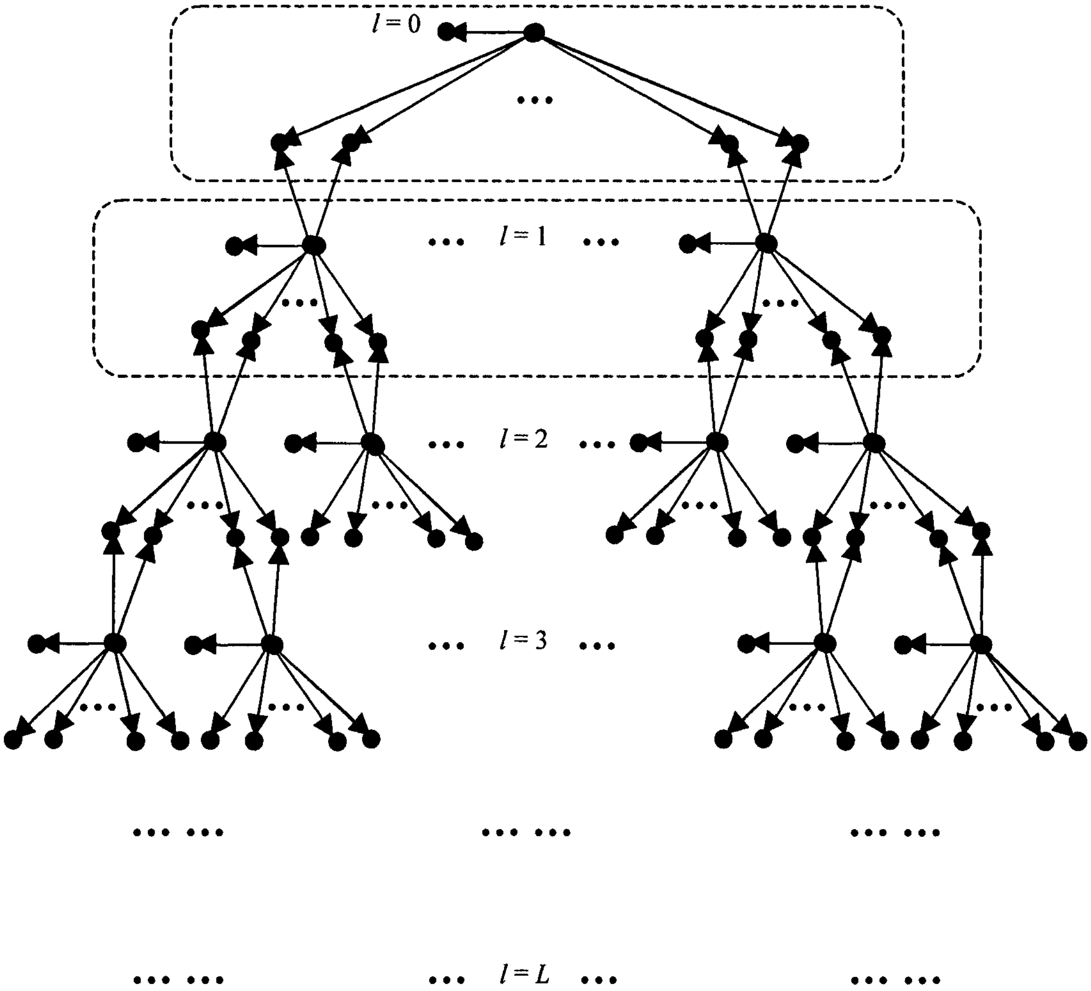

Figure 4.5 DRT topology.

4.1.2 Total Number of Piconets in Scatternet

If K is odd, in the final scatternet, except for the first level in the root piconet of the tree structure, it is like a $(\frac{K-1}{2} - 1)$-ary tree topology because each piconet uses one uplink (with two bridges) to one parent piconet and $(\frac{K-1}{2} - 1)$ downlinks (each with two bridges) to $(\frac{K-1}{2} - 1)$ child piconets. Let N be the total number of nodes. Because each piconet contains $K + 1$ nodes in which two bridge nodes are used for connecting to one parent piconet, there are $K - 1$ new nodes in each new piconet in the DRT topology. In the root piconet, there are two nodes more because there is no parent piconet to connect to. To calculate P, we use $N - 2$. Thus, the total number of piconets P in the scatternet can be given by

$$P = \left\lceil \frac{N-2}{K-1} \right\rceil, \quad N > 2$$

4.1.3 Diameter of Scatternet

Let l denote the level of the tree topology that considers only the masters in the scatternet and $l \in \{0, 1, 2, \ldots, L\}$, where L denotes the maximum level in the tree. In other words, a master node v is considered to be at level l if there is a path from v to the root of the tree that contains l masters excluding the root. Thus, the root itself is at level 0. For a master at level $l > 0$, all up link bridge nodes are considered to be at the previous level $l - 1$, while all down link bridge nodes are counted at level l. See Figure 4.5 for an illustration of a DRT topology and levels.

Let N_l denote the total number of nodes in level l. Let P_l denote the total number of piconets in level l, where a piconet is considered to be in level l if its master is at level l. We can get the following relations:

For $l = 0$, $P_l = P_0 = 1$, and $N_l = N_0 = K + 1$, which is the total number of nodes in the root piconet.

For $l = 1$, $P_l = P_1 = \dfrac{K-1}{2}$, since the master at $l = 0$ contributes $\dfrac{K-1}{2}$ child piconets at level 1. Since each master at level 1 contributes $(K - 1)$ nodes at level 1, we have $N_1 = P_1(K-1) = \dfrac{K-1}{2}(K-1) = \dfrac{(K-1)^2}{2}$.

For levels $l \geq 2$, each master at $l - 1$ contributes $\left(\dfrac{K-1}{2} - 1\right)$ child piconets. Thus $P_l = P_{l-1}\left(\dfrac{K-1}{2} - 1\right)$. As above $N_l = P_l(K-1)$.

Thus, for $l = L$, where $L \geq 2$ is the maximum number of levels in the tree, we have

$$P_l = P_L = P_{L-1}\left(\frac{K-1}{2}-1\right) = \frac{K-1}{2}\left(\frac{K-1}{2}-1\right)^{L-2}\left(\frac{K-1}{2}-1\right) = \frac{K-1}{2}\left(\frac{K-1}{2}-1\right)^{L-1},$$

and

$$N_L = P_L(K-1) = \frac{(K-1)^2}{2}\left(\frac{K-1}{2}-1\right)^{L-1}.$$

Therefore, the total number of piconets P is

$$P = \sum_{l=0}^{L} P_l$$

$$= 1 + \frac{K-1}{2} + \frac{K-1}{2}\left(\frac{K-1}{2}-1\right) + \ldots + \frac{K-1}{2}\left(\frac{K-1}{2}-1\right)^{L-1}$$

$$= 1 + \frac{\frac{K-1}{2}\left[1-(\frac{K-1}{2}-1)^L\right]}{1-(\frac{K-1}{2}-1)} = 1 + \frac{K-1}{2} \times \frac{1-(\frac{K-1}{2}-1)^L}{1-(\frac{K-1}{2}-1)}$$

Thus, we get

$$1 + \frac{K-1}{2} \times \frac{1-(\frac{K-1}{2}-1)^L}{1-(\frac{K-1}{2}-1)} = P$$

$$\left(\frac{K-1}{2}-1\right)^L = 1 - 2 \times \frac{P-1}{K-1} \times \left(2 - \frac{K-1}{2}\right)$$

Consider the situation of the last level not full filled and $P = \left\lceil \frac{N-2}{K-1} \right\rceil$ and $N > 2$, we get L as follows

$$L = \left\lceil \frac{\log\left[1 + \frac{P-1}{K-1}(K-5)\right]}{\log\left(\frac{K-1}{2}-1\right)} \right\rceil = \left\lceil \frac{\log\left[1 + \frac{\left\lceil \frac{N-2}{K-1} \right\rceil - 1}{K-1}(K-5)\right]}{\log\left(\frac{K-1}{2}-1\right)} \right\rceil, \ N > 2$$

The diameter D of the DRT topology is given as follows

When the maximum number of levels in the tree $L = 0$,

If $N = 0$, then $P = 0$ and $D = 0$

If $N = 1$, then $P = 1$ and $D = 0$

If $N = 2$, then $P = 1$ and $D = 1$

If $3 \leq N \leq K + 1$, then $P = 1$ and $D = 2$

When the maximum number of levels in the tree $L = 1$,

If $N = (K + 1) + 1$, then $D = 2 + 4(L - 1) + 1 = 3$.

If $(K + 1) + 2 \leq N \leq (K + 1) + (K - 1)$, then $D = 2 + 4(L - 1) + 2 = 4$.

If $N = (K + 1) + (K - 1) + 1$, then $D = 2 + 4(L - 1) + 3 = 5$.

If $(K+1)+(K-1)+2 \leq N \leq (K+1)+(K-1)\dfrac{K-1}{2}$,

then $D = 2 + 4(L-1) + 4 = 2 + 4L - 4 + 4 = 2 + 4L = 6$.

Let D_i be the diameter of the DRT with i full levels. Consider now a tree with $i + 1$ full levels.

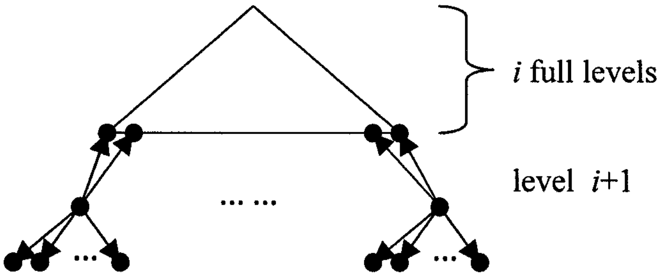

Figure 4.6 Diameter D_i of DRT topology.

Figure 4.6 makes it clear that $D_{i+1} = D_i + 4$ where $D_0 = 2$ at root piconet. Thus, we have $D_L = 4L + D_0 = 4L + 2$ for $L \geq 0$. Now we consider the situations where the levels are not full. Starting from a tree of $L - 1$ full levels, there are four cases to consider as we add new nodes at level L, each case increasing the diameter by 1.

Case (1) involves adding a master node to a previously full tree of $L - 1$ levels, as shown in Figure 4.7(a), and increases the diameter by 1. Case (2) involves adding slaves to this master and filling up the first subtree corresponding to the first pair of slaves in the root piconet. It is shown in Figure 4.7(b), and increases the diameter by 1. Case (3) involves adding a single master to the bottom of the second subtree corresponding to the second pair of slaves in the root piconet. This is shown in Figure 4.7(c), and increases the diameter by 1. Case (4) is about all trees obtained by adding further nodes at level L until the level is fully filled. It is shown in Figure 4.7(d), and increases the diameter D again by 1.

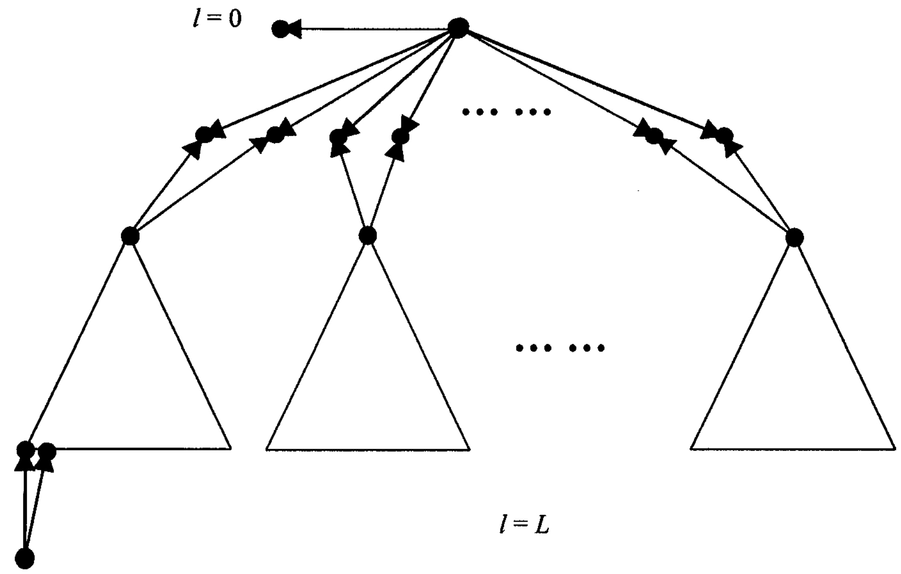

Figure 4.7(a) Adding the first master at level L increases D by 1.

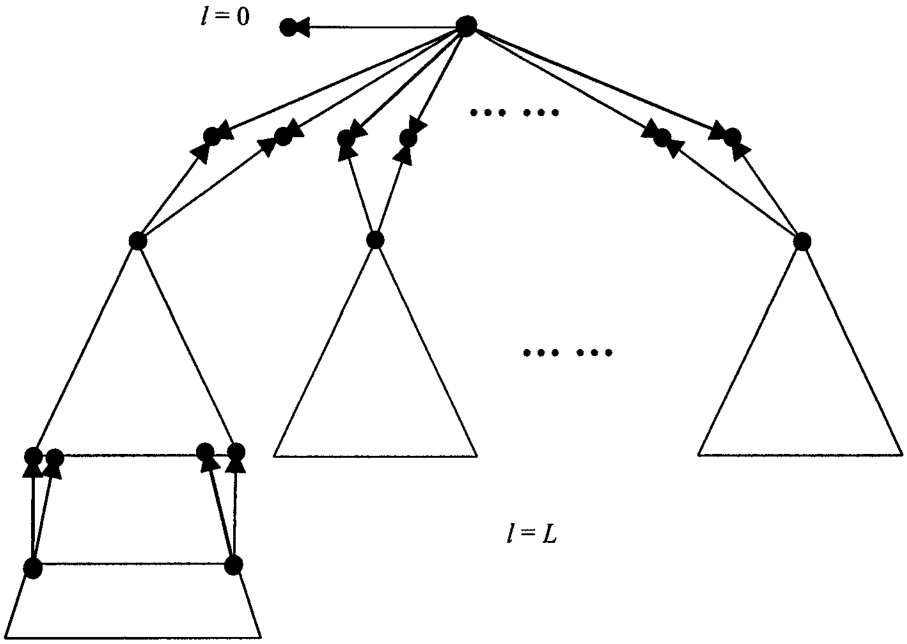

Figure 4.7(b) Filling up the first subtree of root at level L increases D by 1.

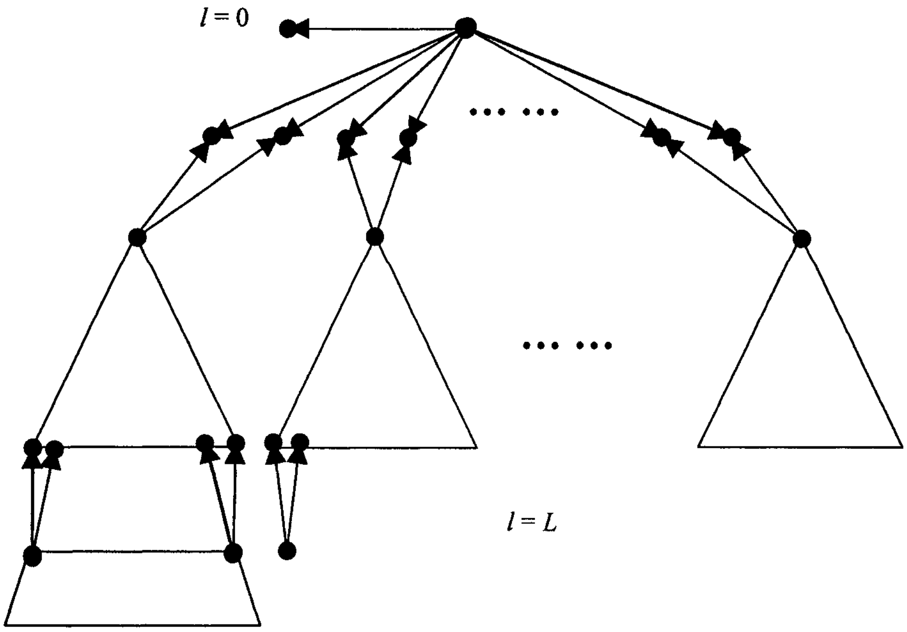

Figure 4.7(c) Adding a master to the second subtree of root at level L increases D by 1.

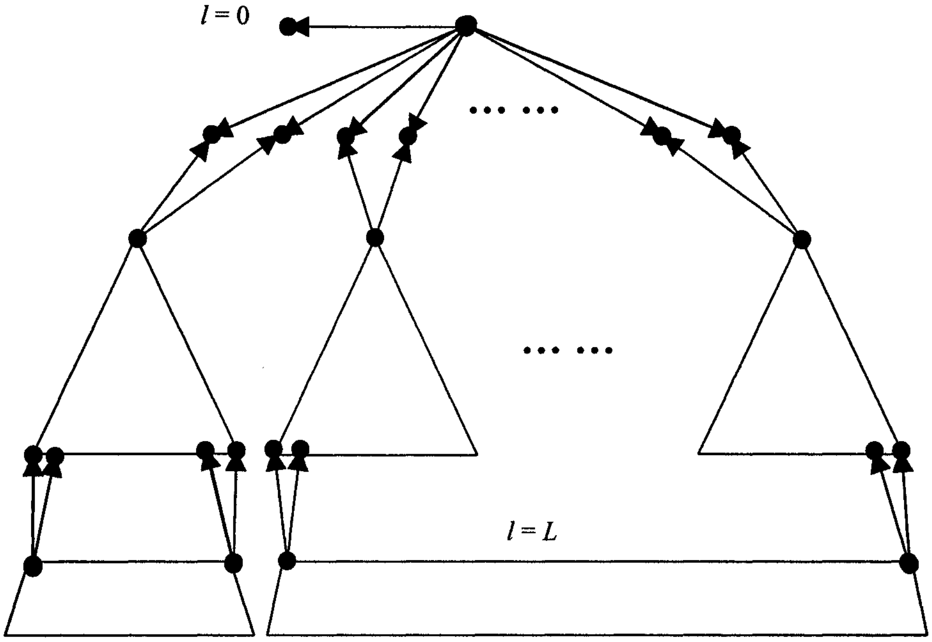

Figure 4.7(d) Filling up level L increases D by 1.

When the maximum number of levels in the tree $L = 2$,

If $N = (K+1) + \frac{(K-1)^2}{2} + 1$, then $D = 2 + 4(L-1) + 1 = 7$.

If $(K+1) + \frac{(K-1)^2}{2} + 2 \leq N \leq (K+1) + \frac{(K-1)^2}{2} + 2(K-1)$,

then $D = 2 + 4(L-1) + 2 = 8$.

If $N = (K+1) + \frac{(K-1)^2}{2} + 2(K-1) + 1$, then $D = 2 + 4(L-1) + 3 = 9$.

If $(K+1) + \frac{(K-1)^2}{2} + 2(K-1) + 2 \leq N$

$$\leq (K+1) + \frac{(K-1)^2}{2} + \frac{(K-1)^2}{2}\left(\frac{K-1}{2} - 1\right),$$

then $D = 2 + 4(L-1) + 4 = 2 + 4L = 10$.

When the maximum number of levels in the tree $L = 3$,

If $N = (K+1) + \frac{(K-1)^2}{2} + \frac{(K-1)^2}{2}\left(\frac{K-1}{2} - 1\right) + 1$, then $D = 2 + 4(L-1) + 1 = 11$.

If $(K+1) + \frac{(K-1)^2}{2} + \frac{(K-1)^2}{2}\left(\frac{K-1}{2} - 1\right) + 2 \leq N$

$$\leq (K+1) + \frac{(K-1)^2}{2} + \frac{(K-1)^2}{2}\left(\frac{K-1}{2} - 1\right) + 2^2(K-1),$$

then $D = 2 + 4(L-1) + 2 = 12$.

If $N = (K+1) + \frac{(K-1)^2}{2} + \frac{(K-1)^2}{2}\left(\frac{K-1}{2} - 1\right) + 2^2(K-1) + 1$,

then $D = 2 + 4(L-1) + 3 = 13$.

If $(K+1) + \frac{(K-1)^2}{2} + \frac{(K-1)^2}{2}\left(\frac{K-1}{2} - 1\right) + 2^2(K-1) + 2 \leq N$

$$\leq (K+1) + \frac{(K-1)^2}{2} + \frac{(K-1)^2}{2}\left(\frac{K-1}{2}-1\right) + \frac{(K-1)^2}{2}\left(\frac{K-1}{2}-1\right)^2,$$

then $D = 2 + 4(L-1) + 4 = 2 + 4L = 14$.

In general, when the maximum number of levels in the tree $L \geq 1$, the diameter D of the DRT topology is given as follows:

If $N = (K+1) + \frac{(K-1)^2}{2}\sum_{i=0}^{L-2}\left(\frac{K-1}{2}-1\right)^i + 1$,

then $D = 2 + 4(L-1) + 1 = 4L - 1$.

If $(K+1) + \frac{(K-1)^2}{2}\sum_{i=0}^{L-2}\left(\frac{K-1}{2}-1\right)^i + 2 \leq N$

$$\leq (K+1) + \frac{(K-1)^2}{2}\sum_{i=0}^{L-2}\left(\frac{K-1}{2}-1\right)^i + 2^{L-1}(K-1),$$

then $D = 2 + 4(L-1) + 2 = 4L$.

If $N = (K+1) + \frac{(K-1)^2}{2}\sum_{i=0}^{L-2}\left(\frac{K-1}{2}-1\right)^i + 2^{L-1}(K-1) + 1$,

then $D = 2 + 4(L-1) + 3 = 4L + 1$.

If $(K+1) + \frac{(K-1)^2}{2}\sum_{i=0}^{L-2}\left(\frac{K-1}{2}-1\right)^i + 2^{L-1}(K-1) + 2 \leq N$

$$\leq (K+1) + \frac{(K-1)^2}{2}\sum_{i=0}^{L-1}\left(\frac{K-1}{2}-1\right)^i,$$

then $D = 2 + 4(L-1) + 4 = 4L + 2$.

4.1.4 Example

If $K = 7$, then in the DRT topology:

$$P = \left\lceil \frac{N-2}{6} \right\rceil, \quad N > 2$$

$$L = \left\lceil \frac{\log\left(1 + \frac{P-1}{3}\right)}{\log 2} \right\rceil$$

For $0 \le L \le 1$,

$D = 2$, when $3 \le N \le 8$,

$D = 3$, when $N = 9$,

$D = 4$, when $10 \le N \le 14$,

$D = 5$, when $N = 15$,

$D = 6$, when $16 \le N \le 26$,

For $L = 2$,

$D = 4L - 1 = 7$, when $N = 8 + 18 + 1 = 27$,

$D = 4L = 8$, when $8 + 18 + 2 \le N \le 8 + 18 + 2 \times 6$, or $28 \le N \le 38$,

$D = 4L + 1 = 9$, when $N = 8 + 18 + 2 \times 6 + 1 = 39$,

$D = 4L + 2 = 10$, when $8 + 18 + 2 \times 6 + 2 \le N \le 8 + 18(2^1 + 2^0)$, or $40 \le N \le 62$.

In Figure 4.8 we can see that

$$N = 36,\ P = \left\lceil \frac{36-2}{6} \right\rceil = \lceil 5.67 \rceil = 6,\ L = \left\lceil \frac{\log\left(1 + \frac{6-1}{3}\right)}{\log 2} \right\rceil = \lceil 1.42 \rceil = 2,\ D = 4L = 8.$$

Compare this with the following recursively fully connected mesh topology where $P = 8, D = 4$.

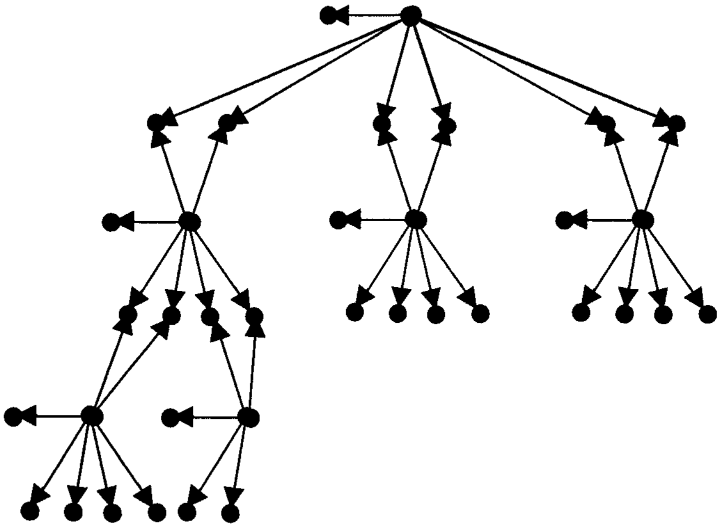

Figure 4.8 DRT topology with $K = 7$ and $N = 36$.

4.2 Recursively Fully Connected Mesh Topology of Scatternets

4.2.1 Description of RFCM Topology

A Bluetooth scatternet with a Fully Connected Mesh (FCM) topology is one in which there is a link between every pair of piconets [11]. Some network topologies while not fully connected, still aim for many connections between piconets and can be called mesh topologies.

The advantages of mesh topologies are more links, better connectivity, better balance to avoid traffic bottleneck, greater reliability and robustness. The disadvantages are more piconets and increased complexity of routing.

Suppose $K = 7$, the basic fully connected mesh scatternet unit with $N = 35$ is given in Figure 4.9, where there are 35 devices (nodes) in seven piconets with a bridge node connecting every pair of piconets. The network diameter D is four, which is optimal for the size of the scatternet. Each master has seven slaves, six slaves are bridge nodes to connect to the remaining six piconets and one slave is reserved for expanding the mesh. We call this unit the *open form* of the recursively fully connected mesh (RFCM) topology at level 0. We can obtain the *closed form* of the RFCM topology from this by adding a master and connecting to all available K slaves as shown in Figure 2.4. No further nodes can be added to the closed form RFCM topology.

We can use the open form RFCM topology at level 0 to construct an RFCM topology with an arbitrary number of nodes N, in a recursive manner as described below.

Essentially, at level $l + 1$, we use K open form RFCM scatternet units of level l, and connect each pair of units with a bridge node. This gives the open form of the level $l + 1$ RFCM scatternet. To get the closed form, we can add one master node and connect to all K units at level l. Figure 4.10 shows the open form of the level l scatternet and Figure 4.11 shows the open form of the level $l + 1$ scatternet.

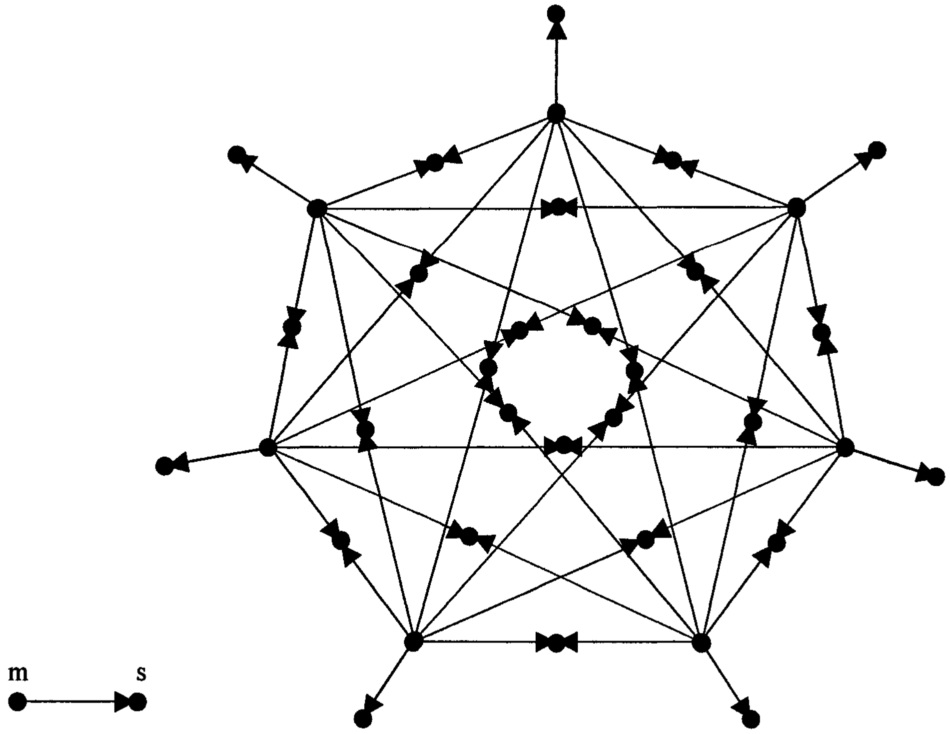

Figure 4.9 The basic unit of the RFCM scatternet topology ($K = 7$, $N = 35$ and $P = 7$).

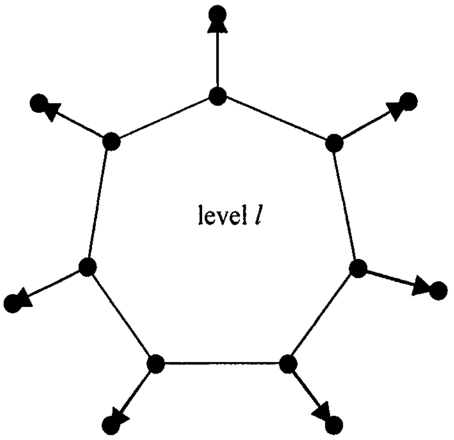

Figure 4.10 RFCM topology at level l ($l \geq 1$ and $K = 7$).

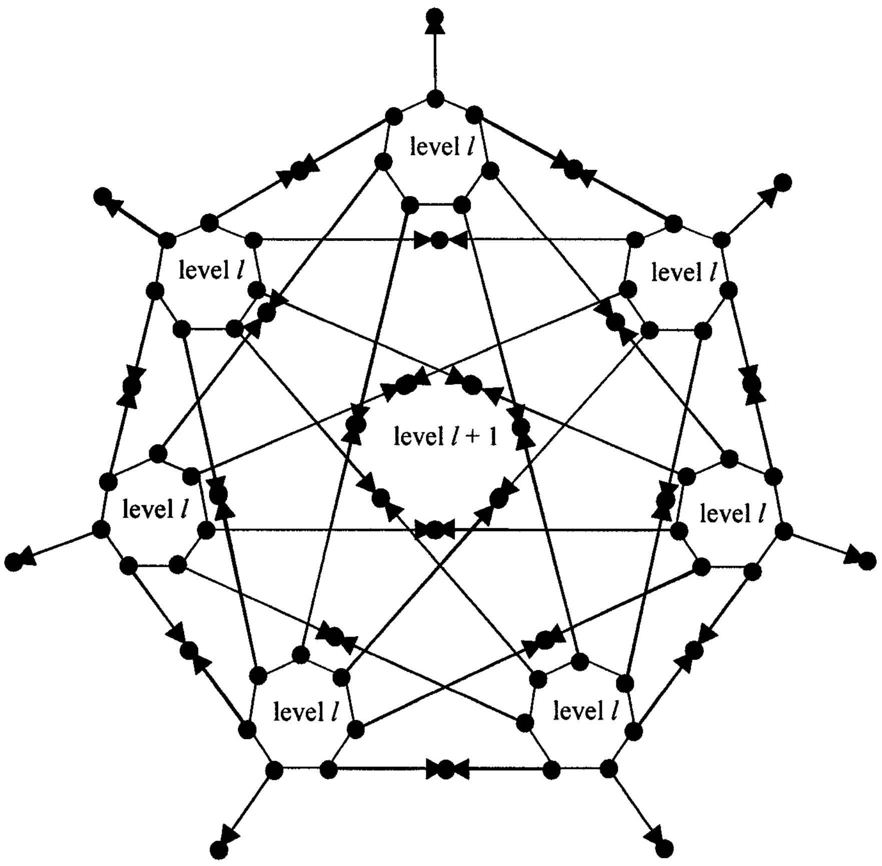

Figure 4.11 RFCM topology at level $l + 1 = L$ ($K = 7$).

For the closed form RFCM topology at level 0, according to Salonidis *et al.* [11], the relation between the number of piconets P and the number of nodes N (where $K = 7$) is

$$P = \left\lceil \frac{17 - \sqrt{289 - 8N}}{2} \right\rceil, \qquad 1 \le \mathrm{N} \le 36$$

The diameter D of the closed form RFCM scatternet topology ($L = 0$) is

$D \le 4$, when $1 \le N \le 36$

In detail,

$D = 0$, when $N = 1$,
$D = 1$, when $N = 2$,
$D = 2$, when $3 \leq N \leq 8$,
$D = 3$, when $N = 9$,
$D = 4$, when $10 \leq N \leq 36$.

4.2.2 Total Number of Piconets in Scatternet

The above expressions are based on the current Bluetooth specification in which the number of slaves in a piconet (denoted as K) is equal to seven. Here we want to get the general relationship among K, N, and P.

Given a number of Bluetooth nodes N and the following conditions:

1. The resulting scatternet is fully connected (every master is connected to all other masters via a bridge).

2. Two masters (or two piconets) share only one bridge node, *i.e.* bridge node degree is 2. A bridge node may connect only two piconets.

3. The maximum number of slaves in a piconet is K.

First we observe that the maximum number of nodes under these conditions is $\frac{(K+1)(K+2)}{2}$. To see this consider the first piconet, which has $K + 1$ nodes. The second piconet must use an existing slave as a bridge and can add only K new nodes. Similarly the i^{th} piconet can add $K + 2 - i$ new nodes. The last piconet adds a single new node, which is a master connecting to all previous K piconets by bridges. No more nodes can be added without violating degree constraints. Thus the maximum possible number of nodes is $\sum_{i=1}^{K+1} i = \frac{(K+1)(K+2)}{2}$.

We will now prove that the minimum number of piconets P is given by the relation:

$$P = \left\lceil \frac{(2K+3) - \sqrt{(2K+3)^2 - 8N}}{2} \right\rceil, \qquad 1 \le N \le \frac{(K+1)(K+2)}{2}$$

Suppose we fix P the number of piconets (masters) in the scatternet. Each piconet i has n_i slaves, consisting of s_i pure slaves and b_i bridges. Thus:

$$n_i = s_i + b_i, \quad 1 \le i \le P \tag{4.1}$$

The maximum number of slaves in a piconet is K:

$$(n_i \le K, \text{ where } 1 \le i \le P) \tag{4.2}$$

According to conditions 1 and 2, each master should be connected to all other masters (condition 1) through only one bridge node (condition 2).

Thus each master will have $b_i = P - 1$ bridges and $s_i = n_i - (P - 1)$ pure slaves.

Also the total number of masters in the scatternet is P and the total number of bridges should be $P(P - 1)/2$ (condition 2). Therefore the following relation holds:

$$P + \sum_{i=1}^{P} s_i + \frac{P(P-1)}{2} = N, \qquad 0 \le s_i \le K - (P-1) \; \forall \, i \tag{4.3}$$

where the sum terms of the LHS are the total number of assigned masters, pure slaves and bridge slaves in the scatternet respectively.

Equation (4.3) reflects the allowable values for P and N based on the scatternet formation conditions 1 – 3. We see that for a fixed P, there is an associated range of values of N that can be covered depending on the possible sets of values s_i.

For example, when there is one piconet, a range of number of nodes from $N = 1$ up to $N = K + 1$ can be accommodated. When there are two piconets, a range of number of nodes from $N = (K + 1) + 1$ to $N = 2(K + 1) - 1$ (where the two masters are connected by a common bridge and each master has $K - 1$ pure slaves) can be accommodated. If the number of nodes $N \geq 2(K + 1)$, then they cannot be supported by only 2 masters because the conditions 1 - 3 will be violated and equation (4.1) will not hold.

The "maximal" set $s_i = K - (P - 1)$ yields the maximum N that can be supported by a specific P. For the values of the maximal set, equation (4.3) becomes:

$$P + \sum_{i=1}^{P} [K - (P - 1)] + \frac{P(P-1)}{2} = N \tag{4.4}$$

$$P^2 - (2K + 3)P + 2N = 0$$

Solving (4.4) for P and keeping the "–" root solution we get:

$$P = f^{-1}(N) = \left\lceil \frac{(2K+3) - \sqrt{(2K+3)^2 - 8N}}{2} \right\rceil, \quad 1 \leq N \leq \frac{(K+1)(K+2)}{2} \tag{4.5}$$

4.2.3 Diameter of Scatternet

Let l denote the level in the RFCM topology where $l \in \{0, 1, 2, \ldots, L\}$, and L denotes the maximum level in the RFCM topology. Let N_l, P_l, and D_l denote the total number of nodes, the total number of piconets, and the diameter of a closed form RFCM scatternet filled upto L levels.

Then when $L = 0$, we have

$$N_0 = \frac{(K+1)(K+2)}{2},\ P_0 = K + 1, \text{ and } D_0 = 4$$

When $L \geq 1$, to obtain P_L, we have to use the open form RFCM scatternet of level $L-1$ as a basic unit. Since this is obtained by removing the last node, a master, we are left with $(P_{L-1} - 1)$ piconets. This unit can be multiplied K times, with the final addition of a single master to obtain the complete scatternet with L levels. Thus,

$$P_L = K(P_{L-1} - 1) + 1$$

It is easy to see that $P_L = K^{L+1} + 1$.

Next, to derive N_L, observe that each piconet in the scatternet contributes one master and K slaves, that are shared between two piconets. Thus, each piconet contributes $1 + \frac{K}{2} = \frac{K+2}{2}$ nodes.

Therefore,

$$N_L = P_L \frac{K+2}{2} = \frac{(K^{L+1}+1)(K+2)}{2}$$

Finally, the diameter in a level L scatternet is the maximum distance between two level $L - 1$ RFCM scatternet units that are components of the level L scatternet. Since these must be connected by a bridge node, it follows that

$$D_L = 2D_{L-1} \quad \text{for } L \geq 1$$

Since $D_0 = 4$, we have $D_L = 2^{L+2}$

Finally, to derive L, observe that

$$\frac{(K^{L+1}+1)(K+2)}{2} = N$$

$$K^{L+1} = \frac{2N}{K+2} - 1$$

$$L = \left\lceil \frac{\log\left(\frac{2N}{K+2} - 1\right)}{\log K} - 1 \right\rceil,$$

The diameter of a full RFCM scatternet with L levels is

$$D_L = 2^{L+2}$$

The number of nodes, the number of piconets, and diameter of a RFCM scatternet topology with L levels completely filled are summarized in Table 4.1.

N_L	$\frac{(K^{L+1}+1)(K+2)}{2}$
P_L	$K^{L+1}+1$
D_L	2^{L+2}

Table 4.1 Parameters for RFCM scatternet topology.

4.2.4 Example

According to current Bluetooth specification with $K = 7$, we can get the following results,

At level $L = 0$, the RFCM topology is shown in Figure 2.4 and Figure 4.9 with

$$N_0 = \frac{(K+1)(K+2)}{2} = \frac{(7+1)(7+2)}{2} = \frac{72}{2} = 36,$$

$$P_0 = K + 1 = 7 + 1 = 8,$$

$$D_0 = 2^{L+2} = 2^2 = 4.$$

At level $L = 1$, the RFCM topology is shown in Figure 4.12 with

$$N_1 = \frac{(K^2+1)(K+2)}{2} = \frac{(7^2+1)(7+2)}{2} = 225, \text{ with open form } N_1 = 224$$

$$P_1 = K^2 + 1 = 7^2 + 1 = 49 + 1 = 50, \text{ with open form } P_1 = 49$$

$$D_1 = 2^{L+2} = 2^3 = 8.$$

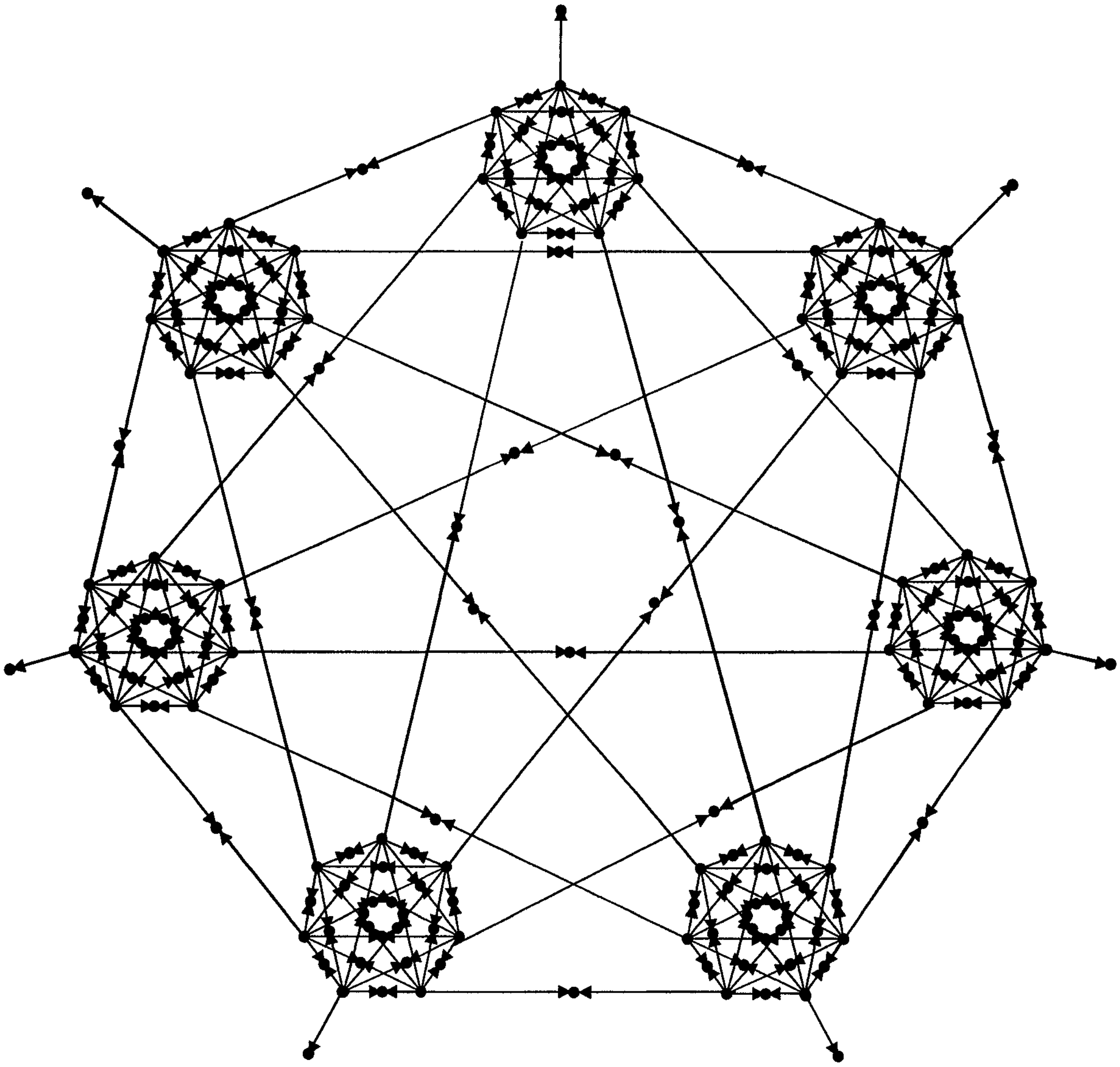

Figure 4.12 RFCM topology at level 1 ($N = 224$, $P = 49$, and $D = 8$).

4.3 Combined Topologies of Scatternets

4.3.1 Description of CMT Topology

Combined topologies are combinations of the basic topologies such as tree and mesh to construct a scatternet.

The idea is to combine the advantages from two or more basic topologies and eliminate the disadvantages from them to get a better scatternet topology according to the performance metrics.

There can be many different combined topologies. We propose the combined mesh-tree (CMT) topology based on the basic fully connected mesh scatternet unit of level 0 as shown in Figure 4.9, which is used as a sub-scatternet in the final scatternet topology. The maximum diameter in the sub-scatternet is four. Note that the basic unit here is the same as in the RFCM topology.

The top or core fully connected mesh sub-scatternet unit acts as a root in the tree structure. There are also parent, child and leaf mesh units in the tree. These definitions are the same as the definitions in a normal tree structure with the node in a normal tree topology being replaced by RFCM unit of level 0 in the CMT topology.

The scatternet with CMT topology until level 1 is shown in Figure 4.13. Except the root unit which can connect to K sub-scatternets, each sub-scatternet can connect up to $K-1$ other sub-scatternets through the $K-1$ bridge nodes to build a ($K-1$)-ary tree structure. The bridge nodes between the sub-scatternets all have degree two and are of S/S type.

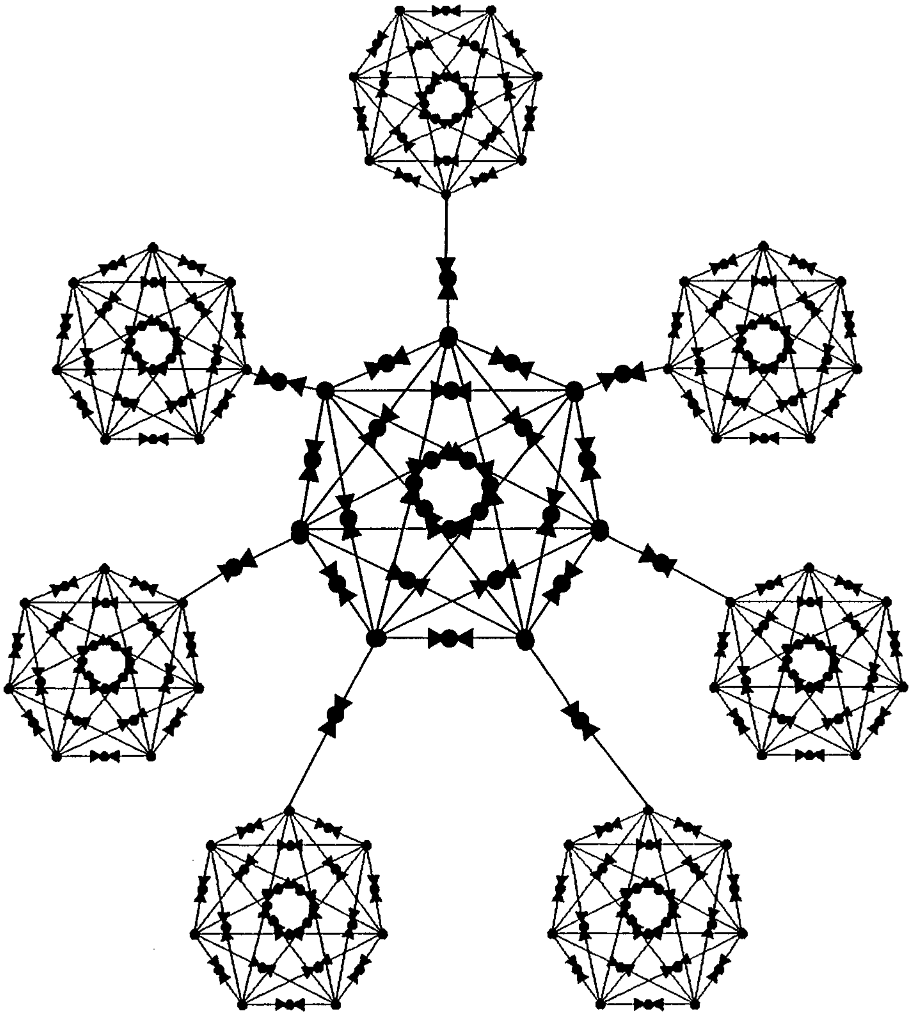

Figure 4.13 Scatternet with CMT topology at level $l = 1$ with $K = 7$.

4.3.2 Total Number of Piconets in Scatternet

Next we derive the total number of piconets in the CMT topology for L levels when the number of nodes is N.

When $L = 0$, and $1 \leq N \leq \dfrac{(K+1)(K+2)}{2}$,

$$P = \left\lceil \frac{(2K+3) - \sqrt{(2K+3)^2 - 8N}}{2} \right\rceil \text{ as shown earlier.}$$

When $L \geq 1$, we have $N > \frac{(K+1)(K+2)}{2}$. Let $N_0 = \frac{(K+1)(K+2)}{2}$, then there is one unit at level 0 which contributes K piconets. Further there are $(N - (N_0 - 1))$ nodes at levels higher than 0, and each unit in these levels uses at most $(N_0 - 2)$ new nodes.Thus, the number of full units at levels higher than 0 is $\left\lfloor \frac{N - (N_0 - 1)}{N_0 - 2} \right\rfloor$, each of which gives K piconets. Finally, there is at most one incomplete unit with N' nodes where $N' = R + 1$, $R = (N - (N_0 - 1)) \bmod (N_0 - 2)$ and $R \neq 0$, which contributes $\left\lceil \frac{(2K+3) - \sqrt{(2K+3)^2 - 8N'}}{2} \right\rceil$ piconets. Thus,

$$P = K + K\left\lfloor \frac{N - (N_0 - 1)}{N_0 - 2} \right\rfloor + \left\lceil \frac{(2K+3) - \sqrt{(2K+3)^2 - 8N'}}{2} \right\rceil$$

where

if $(N - (N_0 - 1)) \bmod (N_0 - 2) \neq 0$,

$N' = (N - (N_0 - 1)) \bmod (N_0 - 2) + 1$,

if $(N - (N_0 - 1)) \bmod (N_0 - 2) = 0$,

$N' = 0$.

4.3.3 Diameter of Scatternet

Let l denote the level of the tree in the CMT topology and $l \in \{0, 1, 2, \ldots, L\}$, where L denotes the maximum level in the CMT. Let N_l denote the number of nodes in level l and P_l denote the number of piconets in level l, assuming that level l is full.

To derive N_L, note that $N_0 = \dfrac{(K+1)(K+2)}{2}$ as shown earlier. Further, as above there are K units at level 1, where each unit uses the open form RFCM unit of level 0, with the bridge node to level 0 not connected at level 1. Therefore $N_1 = K\left(\frac{(K+1)(K+2)}{2} - 2\right)$. Hereafter, using the same reasoning as above

$$N_l = (K-1)N_{l-1} \text{ for } l \geq 2$$

Solving for N_L, we get

$$N_L = K(K-1)^{L-1}\left[\frac{(K+1)(K+2)}{2} - 2\right].$$

Table 4.2 shows the values of N_l for different values of level l.

l	N_l
0	$\frac{(K+1)(K+2)}{2}$
1	$K\left(\frac{(K+1)(K+2)}{2} - 2\right)$
2	$K(K-1)\left(\frac{(K+1)(K+2)}{2} - 2\right)$
3	$K(K-1)^2\left(\frac{(K+1)(K+2)}{2} - 2\right)$
⋮	⋮
$L-1$	$K(K-1)^{L-2}\left(\frac{(K+1)(K+2)}{2} - 2\right)$
L	$K(K-1)^{L-1}\left(\frac{(K+1)(K+2)}{2} - 2\right)$

Table 4.2 The maximal values of N_l at level l.

Therefore, the number of nodes at level $l = 0$ is

$$N_0 = \frac{(K+1)(K+2)}{2}.$$

The total number of nodes N in the scatternet is:

$$N = N_0 - 1 + N_1 + N_2 + N_3 + N_4 + \dots + N_{L-1} + N_L = N_0 - 1 + \sum_{l=1}^{L} N_l$$

$$= \frac{(K+1)(K+2)}{2} - 1 + K\left[\frac{(K+1)(K+2)}{2} - 2\right] + K(K-1)\left[\frac{(K+1)(K+2)}{2} - 2\right] +$$

$$K(K-1)^2\left[\frac{(K+1)(K+2)}{2} - 2\right] + K(K-1)^3\left[\frac{(K+1)(K+2)}{2} - 2\right] + \dots\dots +$$

$$K(K-1)^{L-2}\left[\frac{(K+1)(K+2)}{2} - 2\right] + K(K-1)^{L-1}\left[\frac{(K+1)(K+2)}{2} - 2\right]$$

$$N = \frac{(K+1)(K+2)}{2} - 1 + \frac{K\left[\frac{(K+1)(K+2)}{2} - 2\right]\left[(K-1)^L - 1\right]}{K-2}$$

Thus, we get

$$(K-1)^L = \frac{\left[N - \left(\frac{(K+1)(K+2)}{2} - 1\right)\right](K-2)}{K\left[\frac{(K+1)(K+2)}{2} - 2\right]} + 1$$

Solving for L, we get:

$$L = \left\lceil \frac{\log\left(\frac{\left[N-\left(\frac{(K+1)(K+2)}{2}-1\right)\right](K-2)}{K\left[\frac{(K+1)(K+2)}{2}-2\right]}+1\right)}{\log(K-1)} \right\rceil$$

It is easy to see that $P_0 = K + 1$, if $L = 0$. To find the number of piconets at level 1, we have to use an open form RFCM unit of level 0, which has K free slaves, and can be attached to K other such units at level 1. Thus the total number of piconets at level 1 is K^2. However, for $l \geq 2$, each unit at level $l - 1$ can only be attached to $K - 1$ units at level l. Thus,

$$P_l = (K-1)P_{l-1} \quad \text{for } l \geq 2$$

Solving for P_L at level L, we get

$$P_L = K^2(K-1)^{L-1}$$

Finally, to derive diameter,

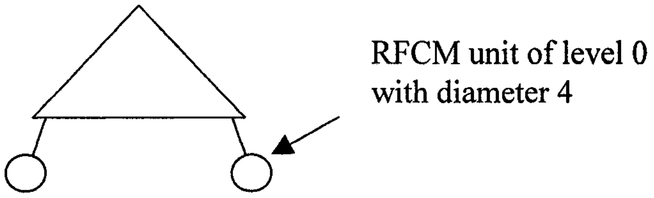

Figure 4.14 Diameter of CMT topology.

It is easy to see from Figure 4.14, $D_0 = 4$ and $D_l = D_{l-1} + 8$ for $l \geq 1$. Thus, we get

$$D_L = 8L + 4$$

Table 4.3 shows the values of N_L, P_L, and D_L for CMT scatternet with L levels. Recall that N_L and P_L are the number of nodes and piconets respectively in a CMT scatternet at level L (not upto L levels) when the level is filled.

N_L	$K(K-1)^{L-1}\left(\frac{(K+1)(K+2)}{2}-2\right)$
P_L	$K^2(K-1)^{L-1}$
D_L	$8L+4$

Table 4.3 Parameters for CMT scatternet topology.

4.3.4 Example

An example of a CMT scatternet with $K = 7$ and $L = 1$ is given in Figure 4.13. If $N = 225$, $K = 7$, $N_0 = 36$, $N' = (N-(N_0-1)) \bmod (N_0-2)+1 = 21$

$$P = K + K\left\lfloor \frac{N-(N_0-1)}{N_0-2} \right\rfloor + \left\lceil \frac{(2K+3)-\sqrt{(2K+3)^2-8N'}}{2} \right\rceil$$

$$= 7 + 7\times 5 + \left\lceil \frac{17-\sqrt{17^2-8\times 21}}{2} \right\rceil = 7+7\times 5+3$$

$$= 45.$$

$$L = \left\lceil \frac{\log\left(\frac{(N-35)5}{238}+1\right)}{\log 6} \right\rceil = \lceil 0.897 \rceil = 1$$

$D_L = 8L + 4 = 12.$

4.4 Algorithms for Scatternet Formation

Three topologies, DRT, RFCM, and CMT, are discussed above in detail for Bluetooth scatternet formation. All three topologies are based on the assumptions that the total number of Bluetooth nodes *N* is not limited, all nodes are in the communication range of each other, all master nodes have at most *K* slaves, all bridge node have S/S type with degree 2, and all nodes are turned on at the same time to form the Bluetooth scatternet, which is the conference scenario.

When all nodes are in range of each other, three phases as in BTCP [11] can be used to form the different scatternets according to the above different topologies. Phase I for coordinator election and Phase III for the actual connection establishment are the same for all algorithms. The only difference is in Phase II for role determination. In Phase II, according to different predefined topologies, the coordinator assigns a role to each node as master, slave, or bridge in the final scatternet. The coordinator connects to the designated masters it selected by paging them and then transmits to each designated master its connectivity list set (SLAVESLIST(x), BRIDGELIST(x)), and instructs the designated masters to start phase III.

4.5 Comparison

In this section, we compare the performance of the 3 topologies we proposed.

4.5.1 Theoretical Bounds on *P* and *D*

Given *N*, we compute the number of piconets *P* and the diameter *D* given by all three topologies, DRT, RFCM, and CMT in Table 4.4. The numbers of piconets in the RFCM and CMT topologies are approximately the same, and twice the number in the DRT topology. The diameter of the RFCM topology is asymptotically larger than that of the other two topologies. Assuming *K* is constant, the values of *P* and *D* for the three topologies in big-oh notation are given in Table 4.5. While the number of piconets in all topologies is comparable, the diameter of the RFCM scatternet grows faster than that of the other two topologies. For $K = 7$, the diameter of the RFCM scatternet is $O(N^{0.36})$, whereas it is $O(\log N)$ for the DRT and CMT scatternets.

	DRT	RFCM	CMT
P	$\frac{N}{K-1}$	$\frac{2N}{K+2}$	$\frac{2N}{K+2}$
D	$\frac{4\log\left(\frac{N}{K}\right)}{\log\left(\frac{K-3}{2}\right)}$	$N^{\log_K 2}$	$\frac{8\log\left(\frac{N}{K^2}\right)}{\log(K-1)}$

Table 4.4 The approximate values of *P* and *D* for DRT, RFCM, and CMT topologies.

	DRT	RFCM	CMT
P	$O(N)$	$O(N)$	$O(N)$
D	$O(\log N)$	$O(N^{0.36})$	$O(\log N)$

Table 4.5 P and D for DRT, RFCM, and CMT topologies, assuming $K = 7$.

4.5.2 Empirical Values of *P* and *D*

Table 4.6 gives the values of P and D for increasing number of nodes for all three topologies with $K = 7$. The empirical results confirm the bounds obtained theoretically in finding that the number of piconets in the RFCM and CMT topologies are very close, but both are significantly higher than that in the DRT topology. Note that RFCM has the best value of diameter for the networks with upto 1000 nodes, after which CMT has the lowest diameter. Similarly, the DRT topology has a better diameter than RFCM consistently when the number of nodes is greater than 20,000. It also appears that while the diameters of the DRT and CMT topologies have a similar rate of growth, the diameter of the CMT topology is always smaller than that of the DRT topology.

N	*P*			*D*		
	DRT	RFCM	CMT	DRT	RFCM	CMT
100	17	20	20	14	8	12
200	33	43	40	18	8	12
300	50	65	61	20	16	16
400	66	86	81	22	16	16
500	83	108	102	22	16	20
1000	167	219	205	26	16	20
2000	333	442	411	30	32	24
5000	833	1108	1030	36	32	28
10000	1667	2217	2059	40	32	28
20000	3333	4439	4118	44	64	36
50000	8333	11100	10293	50	64	36
100000	16667	22215	20588	54	128	40

Table 4.6 The values of *P* and *D* for DRT, RFCM, and CMT topologies.

4.5.3 *P-N* Curve and *D-N* Curve

Figure 4.15, 4.16, and 4.17 give the *P–N* curves for all 3 topologies. Since the number of piconets is actually a linear function of *N*, using a linear fit approximation is reasonable, and we see that the number of piconets in the DRT topology is less than that in the RFCM and CMT topologies. The *P–N* curves of the latter two are very similar. The maximum value of N considered is 250 and we use $K = 7$ as in the current Bluetooth specification.

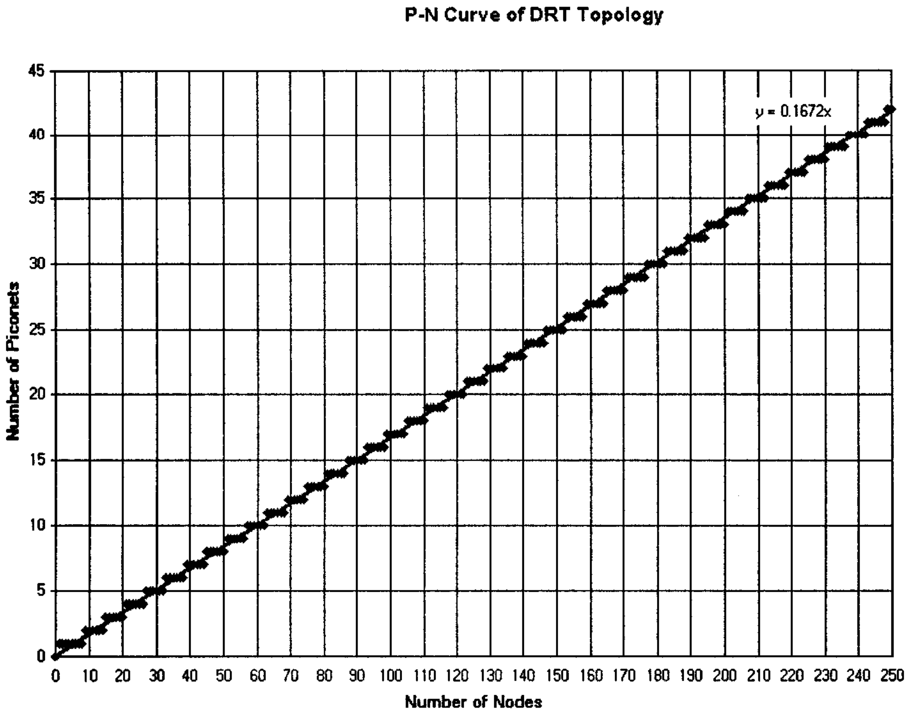

Figure 4.15 P-N curve of DRT topology with $K = 7$ and $a_1 = 0.1672$.

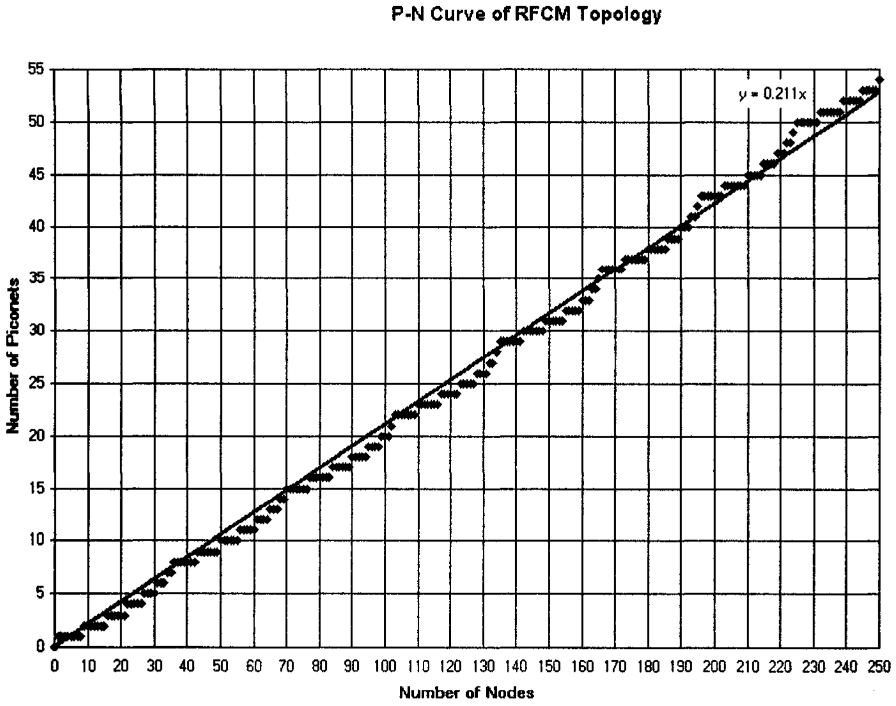

Figure 4.16 *P*-*N* curve of RFCM topology with $K = 7$ and $a_1 = 0.211$.

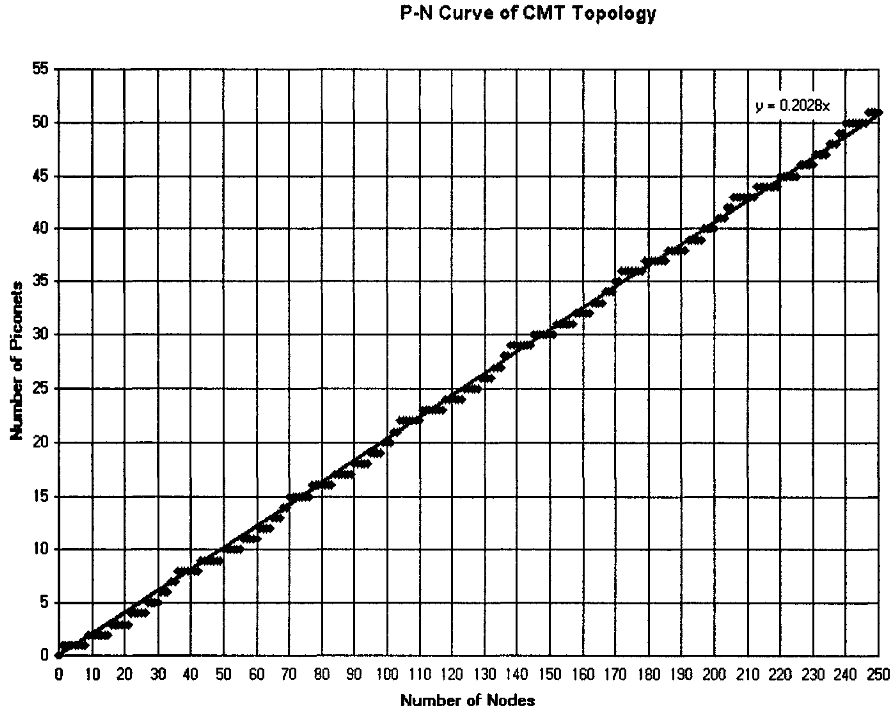

Figure 4.17 *P*-*N* curve of CMT topology with $K = 7$ and $a_1 = 0.2028$.

The diameters of all three topologies are clearly non-linear functions of *N*, and so the linear fit does not give a good approximation of the function. To get a good approximation, one should obtain more data points and use a higher order fit approximation. Figures 4.18, 4.19, and 4.20 give the *D–N* curves given by approximating by a polynomial of degree 3. The coefficients show that the RFCM topology has smaller diameter than the remaining two, which as Table 4.6 shows, is true for the values of *N* plotted. However, as *N* grows, the diameter of the RFCM topology will be worse than that of the other two. This will not be accurately predicted by the *D–N* curve here. To obtain a more accurate *D–N* curve, it is necessary to consider more data points.

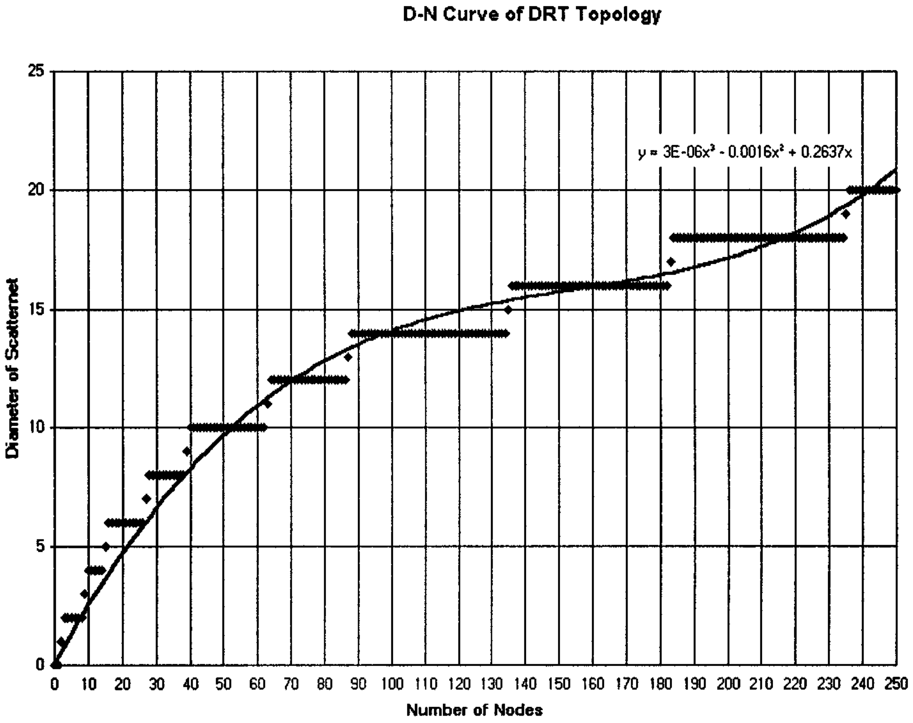

Figure 4.18 *D-N* curve of DRT topology with $K = 7$.

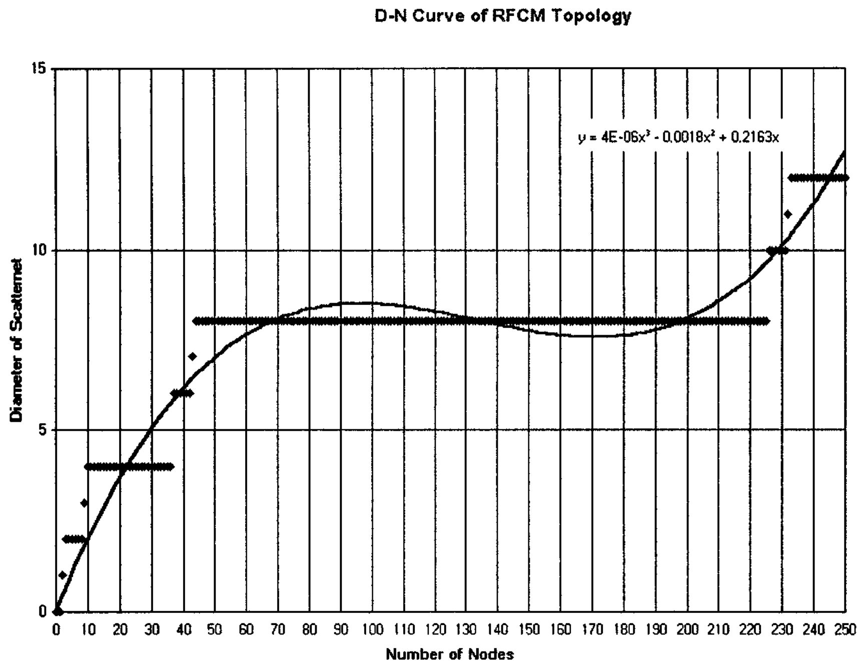

Figure 4.19 *D-N* curve of RFCM topology with $K = 7$.

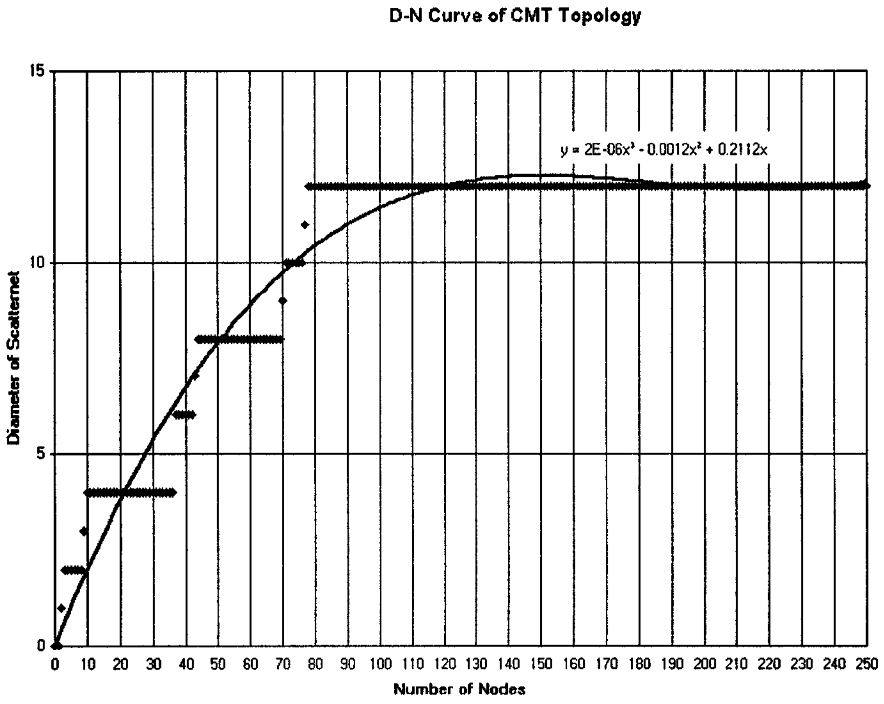

Figure 4.20 *D-N* curve of CMT topology with $K = 7$.

4.5.4 Response to Node Leaving the Scatternet

In the case of any node leaving the scatternet, the three topologies, DRT, RFCM, and CMT, all can easily deal with it and keep the scatternet still connected.

In the DRT topology, if one slave node leaves the scatternet, no change is required to the scatternet. If one of the bridge nodes leaves the scatternet, either the scatternet does not change because the other bridge node keeps the scatternet still connected or makes a slave node as the new bridge node. Finally if the master node leaves the scatternet, the scatternet simply makes a slave node as the new master. So the changes required as a result of nodes leaving are minimal.

In the RFCM topology, if one slave node leaves the scatternet, no change is required to the scatternet. If one bridge node leaves the scatternet, either the scatternet does not change because it is still connected, or it makes one slave node as the new bridge node. If one master node leaves the scatternet, either the scatternet is still connected and therefore does not change or simply makes one slave node as the new master node. So the changes required as a result of nodes leaving are minimal.

It is the same in the CMT topology: if one slave node leaves the scatternet, the scatternet does not have to change. If one bridge node or one master node leaves the scatternet, either the scatternet is still connected and so no change is required or it makes one slave node as the new bridge node or new master node. So the changes required as a result of nodes leaving are minimal.

5 Conclusion and Future Work

This major report makes three contributions. First of all, details of different scatternet topologies and several recent related research papers on scatternet formation are discussed, summarized and critiqued individually. Advantages and disadvantages of the protocols in each paper are given. Second, general guidelines and a set of performance metrics for scatternet formation are proposed and summarized. The performance metrics are categorized into two classes, namely static performance metrics and dynamic performance metrics. The static performance metrics are decided only by the scatternet topology and the dynamic performance metrics are based on the actual functioning of the scatternet or the scatternet formation protocol. The report proposes two curves, *i.e.* the *P-N* curve and the *D-N* curve as static performance metrics which influence also the dynamic performance metrics. Finally, according to the general guidelines and keeping the static/dynamic performance metrics in mind, three new scatternet topologies are proposed and some metrics such as the number of piconets P in a scatternet and the diameter D of a scatternet are evaluated for them. The three proposed topologies can easily deal with any node leaving the scatternet. With the three new topologies, the scatternet will have higher connectivity and will be more robust.

There are many interesting directions for future work suggested by the work done here. One direction would be to make a dynamic simulation to estimate the dynamic performance of the three proposed topologies. It would also be interesting to study the case when not all nodes are in transmission range of each other. All nodes will use only the knowledge of their immediate neighbors to form the different scatternets according to the different topologies. The scatternets can use both M/S and S/S type bridges.

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