Three Bluetree Formations for Constructing Efficient Scatternets in Bluetooth [*]

Yuhong Dong and Jie Wu
Dept. of Comp. Sci. and Eng.
Florida Atlantic University
Boca Raton, FL 33431
{ydong, jie}@cse.fau.edu

Abstract

Bluetooth wireless technology is designed as a short-range connectivity solution for personal, portable, and handheld electronic devices. Bluetooth allows a large number of piconets to form a scatternet using bridge nodes that participate in multiple piconets. The scatternet formation for constructing an efficient and practical Bluetooth wireless network is still an open issue. In this paper, we propose three Bluetree algorithms that aim to minimize the overheads introduced by Bluetooth's piconet and multi-hop scatternet. Our modification algorithms use the neighbor's neighbor set and/or neighbor's location to construct the Bluetree to efficiently balance two conflicting goals between the Number of Piconets (NP) and the Average Shortest Path (ASP) ratio. Our simulation results show that the proposed approach outperforms the existing approaches in terms of balancing these two goals. In addition, we study the effect of node density on the scatternet performance.

1 Introduction

The $Bluetooth^{TM}$ wireless technology [1] revolutionizes the personal connectivity market by providing freedom from wired connections - enabling links between mobile computers, mobile phones, portable handheld devices, and connectivity to the Internet. Bluetooth operates in the unlicensed ISM band at 2.4 GHz at a data rate of 720Kb/s. It uses Frequency Hopping (FH) spread spectrum, which divides the frequency band into a number of channels (2.402 - 2.480 GHz yielding 79 channels). Radio transceivers hop from one channel to another in a pseudo-random fashion, determined by the master.

Bluetooth supports up to 8 devices in a *piconet* (1 master and up to 7 slaves). Piconets can combine to form a *scatternet*. Figure 1 shows a scatternet with three piconets, where each node has either a single role (master or slave) or multiple roles (master and slave). A multiple-role node is called a *bridge node*. However, each bridge node will introduce switching overload to bridge two piconets. One objective is to reduce the number of bridge nodes through reducing the Number of Piconets (NP). Another objective is to keep the Average Shortest Path [11] short. Specifically, ASP is defined as the average shortest path length (hop count) among all 2-node pairs in a network. In general, we want to keep ASP ratio, ASP_{tree}/ASP_o, small, where ASP_{tree} and ASP_o are ASP's under the Bluetree and the original network, respectively. ASP ratio and NP are two conflicting goals; a sensitive balance is needed.

In the next section, we will discuss some related work that has been done on Bluetooth scatternet formation. In section 3, we explain our modification algorithm for formating Bluetooth scatternet. Then, in section 4 presents the results of our simulations, where we demonstrate the use of our modification algorithms. Finally, section 5 summarizes the main results and outlines our future research.

2 Related Work

Scatternet formation must be addressed before any routing protocol can be run over Bluetooth. There are two kinds of networks, static and dynamic networks, according to the network nodes' mobility. Static scatternet formation algorithms were presented in [2][3][4], while the scatternet formation algorithms, dealing with the nodes' mobility, were described in [15][13][12][10] [9][8].

Salonidis et al. [2] presented the Bluetooth Topology Construction Protocol (BTCP), which is asynchronous distributed protocol for constructing multi-hop scatternets. The protocol consists of three stages: coordinator election; role determination; actual connection establishment. Initially, each node has a variable of votes equal one, and has no knowledge of its surroundings. In coordinator election stage, any two pair nodes discover each other, build the point to point connection, compare the votes. The node with the larger votes is elected as winner. The winner nodes continue to discover another network node, eventually, the node with the largest votes is selected as leader (or coordinator), which knows all nodes' information in the network. In role determination stage, the leader node then calculates the number of master nodes needed in order to make the network connected, decides the role for each node, informs the selected master nodes of their master assignment and slave-lists, and connects to the master nodes. In the actual connection establishment stage, the selected master nodes

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[*] This work was supported in part by NSF grant 0073736 and EIA 0130806. Contact address: jie@cse.fau.edu

connect with their slaves which are included in their slave-lists. Finally, the networks is connected, and the scatternet is formed. In this protocol, global information is needed to elect the leader, the leader election stage is more time consuming than other stages. It also has limitation of the number of master nodes, which must be less than seven, so that limits the number of piconets in a scatternet. In our paper, we propose two protocols that can generate multi-hop scatternet based only on the local view of each node, and no limitation of the number of piconets in a scatternet.

Cgun-Choong et al. [3] proposed a Bluetooth scatternet with ring structure. All nodes are arranged in a ring structure. Each node belongs to two piconets, acts as a Master-Slave relay, and has exactly two links in total. Initially, all nodes are within direct radio range of each other. The unconnected nodes and multiple lines of nodes are then merged into one single line to form a line consisting of all nodes. Finally, the line is closed to form a ring. The BlueRing has benefits in terms of reliability, ease of packet routing and scheduling, but this algorithm works based only on single-hop networks.

Stojmenovic [4] presented a scatternet formation with dominating set [5] and Yao subgraph [6], which follows bellow procedure: first, each node establishes connection with all of its neighbors that are located within its transmission radius; secondly, if any node A has the node degree in excess of 7, Yao structure construction is then performed on A. A's unit graph is divided into 7 equal angels centered at A, and chooses one closest node from each region. The degree of each node is limited to 7, followed by either elimination of directed edges or the application of reverse Yao construct. Finally, master-slave relations are created by applying higher degree priority (with dominating set membership as the primary key). It is proved that the resulting scatternet remains connected. In this paper, we propose a scatternet formating algorithm based on the Yao graph theory in a different way.

In IEEE 802.11b [14] ad hoc mode, any node can communicate with another as long as they are in radio range of each other, and there are no link setup procedure required. However, a Bluetooth node must join or create a piconet before any packet forwarding. There are several papers, such as [15][13][12][10] [9][8], dealing with the bluetooth scatternet formations which are facilities for wireless ad hoc network routing.

Zaruba et al. [9] proposed to use the Bluetree scatternet formation algorithm to enable the establishment of a mobile ad hoc network. Petrioli et al [8] described the BlueMesh scatternet formation algorithm to build multi-hop ad hoc network. But how scatternet supports node's mobility is not elaborated in both [9] and [8].

Liu et al. [15] suggested building scatternet-route structure by combining scatternet formation with on-demand routing; Kawamoto et al. [12] proposed a two-phase scatternet formation protocol (TPSF) to support dynamic topology changes by constructing a control scatternet and on-demand scatternet. In [15][12], both of them avoid initially to build the entire network with all the Bluetooth nodes; Sun et al. [10] presented an algorithm to embed b-trees into a scatternet which enables such an ad hoc Bluetooth network to be self-routing; Zhen et al. [13] described a distributed 2-stage Bluetooth scatternet formation algorithm that separates network formation from routing. First, a group of neighbor nodes are self-organized into blue-star island. Then, the bridging of blue-star islands is initiated by Routing Triggers from the routing protocol. The blue-star island network formation maintains up-to-date connection of every node in the network. Furthermore, it updates the network topology dynamically, which enables the nodes to leave and join at arbitrary times and hence provides an always ready Bluetooth Ad Hoc Network Group. Because each node only knows the local information, it is difficult to get the global information, this formation algorithm still has difficulties to get the scatternet optimized for mobile ad hoc routing.

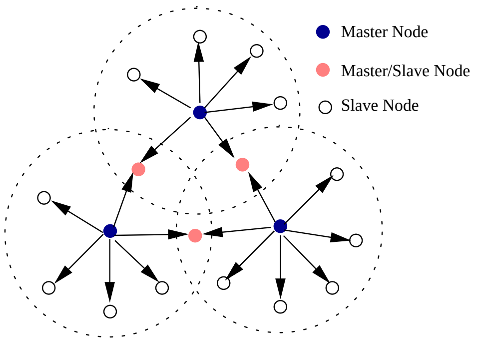

Figure 1. A scatternet with two piconets.

Blueroot Grown Bluetree (BGB), presented by G. Zaruba et al. [7], assumes that each node, upon terminating its boot procedure, is aware of the number and identities (i.e the Bluetooth address) of its neighbors. It also assumes that two nodes are connected if their geographical distance is within a given distance (the corresponding graph is called a *visibility graph*). In Phase 1, if a node is a blueroot, it starts paging its neighbors one by one. If a node is paged and it is not a part of any piconet, it accepts the paging, thus becoming the slave of the paging node; otherwise, it does not respond. This procedure is repeated, until all nodes are assigned to piconets. Once a node has been assigned a role of slave in a piconet, it becomes a master in a new piconet and initiates the paging all of its neighbors one by one. After the Bluetree is formed, during Phase 2, the following approach is initiated at each node, until all nodes satisfy the slave constraint, that is, each master can have up to 7 slaves. Because node connections are based on geometrical distance, when a master m has more than L ($\geq$ 5) slaves, at least two slaves (say $s1$ or $s2$) directly connect to each other. In this case, $s2$ can be removed from m's slave list and becomes the slave of $s1$. After such a branch reorganization, the resulting topology retains the Bluetree properties, and all masters will have at most L slaves (where L is 5).

In this paper, we propose three modifications. In all the modifications, Phase 1 of the Bluetree formation remains the same. Modifications on the methods to enforce the slave constraint occur in Phase 2, and a master can have at most K (where K is 6) slaves. A simulation study is conducted to compare BGB with these modifications.

3 Modification Algorithms

The modifications make use of different neighbor information. Modification 1 (Modi1) requires the knowl-

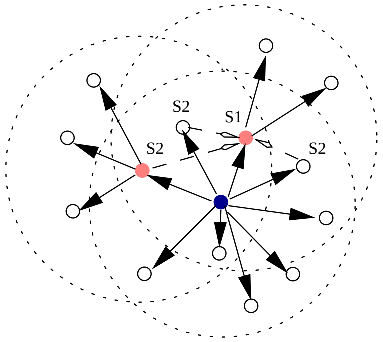

Figure 2. A master selects the nearest neighbor S1 that can cover the maximum number of slaves of the master.

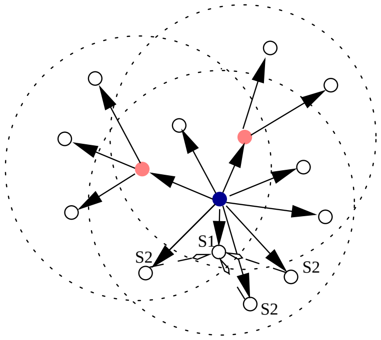

Figure 3. A master selects the nearest neighbor S1 that can cover at least one slave of the master.

edge of the neighbors and neighbor's neighbors. Modification 2 (Modi2) uses the knowledge of relative distance between two nodes which can be determined by relative signal strength. Modification 3 (Modi3) needs the actual geometric positions of the neighbors. In each modification, if a master has more than K slaves, the proposed algorithm is executed at each node until the slave constraint is satisfied.

Modi1. The master m polls the slaves to find out the identities of their neighbors. Using this information, the master m selects a bridge node $s1$, so that it can cover the maximum number of slaves of m. For example, if both $s1$ and $s2$ are neighbors of m, and $s1$ covers (i.e., is connected to) $s2$. Then $s1$ is instructed to make connection with $s2$, and $s2$ is instructed to disconnect the link with master m. The above steps are repeated, unless the number of slaves for m is no more than K. The same algorithm is followed for all the nodes that have more than K slaves. Figure 4 shows a sample Modi2 with K=6.

Modi2. Each master m polls the slaves to determine the identities of the neighbors as well as the distances. Using the distance information, the master m selects slave $s1$ that is the closest to m and that can handle at least one slave of m. $s1$ is then instructed to make connection with the slaves of m, which it covers, and all those slaves are instructed by m to disconnect the links from m. Figure 3 shows a sample Modi2 with K=6.

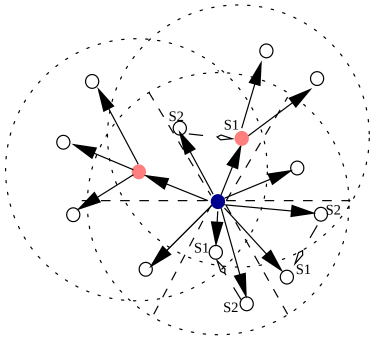

Figure 4. A neighborhood partition with six sectors.

Modi3. This algorithm is based on the positions of nodes. Position information can be found using GPS, which provides location information (longitude, latitude and height) and global timing. A master can have at most K (where K is 6) slaves. For a master m with more than K slaves, draw a circle with m as the center and transmission radius as the radius, and divide the circle into K equal sectors. Then m chooses the closest node $s1$ from each sector. Node m then instructs that node to connect to all the nodes in the corresponding sector, and instructs all the nodes in that region other than $s1$ to disconnect the links with the master m. This process is repeated for all nodes, but in a sequence. The node with the minimum id that has not performed Phase 2 and has more than K slaves performs Phase 2. Figure 4 shows a sample Modi3 with K=6.

4 Performance Evaluation

The performance measures used in this simulation are the Average Shortest Path (ASP) ratio and the Number of Piconets (NP). First, n Bluetooth nodes are randomly located within a rectangular area A of size (20x20 $meter^2$). The nodes are uniformly placed in A and remain stationery during the simulation. Then the visibility graph can be determined according to the Bluetooth radio coverage (20 meters). Next, the scatternet is formed using BGB and the three modifications, separately. Finally, the performance of the resulting scatternet is evaluated and compared based on the metrics introduced above. Simulations are carried out with different choices of n.

We started with 20 nodes in the network, and conducted the simulation based on the four methods, then increased the number of nodes to 40 and 60. We see that the ASP ratio increases about 35 and 38 percent and NP increases about 84 and 43 percent when the number of nodes changes from 20 to 40 and from 40 to 60, respectively.

Table 1 shows the average ASP ratio and NP for the four methods under networks with different node densities. Specifically, the increasing order of ASP ratio based on different node densi-

Table 1. The ASP Ratio and NP of the Bluetree.

	20 Nodes		40 Nodes		60 Nodes	
Algo.	ASP_r	NP	ASP_r	NP	ASP_r	NP
BGB	1.9460	7.0000	2.6711	13.5000	3.6670	18.6667
Modi1	1.8926	6.0000	2.7509	11.0000	3.5947	15.5000
Modi2	1.9019	6.1667	2.6451	11.3333	3.5661	16.5000
Modi3	1.8963	6.6667	2.4600	11.8333	3.3437	17.3333

ties is as follow: Modi1<Modi3<Modi2<BGB for 20 nodes/A; Modi3<Modi2<BGB<Modi1 for 40 nodes/A; and Modi3<Modi2<Modi1<BGB for 60 nodes/A. Under all circumstances of node densities, the increasing order in terms of NP is the following: Modi1<Modi2<Modi3<BGB.

We see that all modifications are better than BGB in reducing both the ASP ratio and NP. Based on decreasing ASP ratio, Modi1 is more suitable for low density networks. Modi3 is suitable for both medium and high density networks, although it has slightly higher NP compared with the other two modifications.

5 Conclusion

In this paper, we have modified the scatternet formation algorithm BGB [7], and proposed three modification algorithms. A simulation study has been conducted to compare scatternet performance under different Bluetree formation algorithms. All modifications can decrease the number of piconets without sacrificing other performance measures.

Right now, we consider only the static network, all nodes have the same transmission radius, and energy level (same life span), and the link between two nodes is symmetric. Although we select the piconet size as less than 7, the resulting multi-hop scatternet is robust and can support a moderate number of nodes to join the network later, without rebuilding the whole network topology.

In future work, we may give more consideration to dynamic networks with mobile wireless ad hoc features, such as node moving, node dying, new node joining, and the issue of how to solve the hidden terminal and exposed terminal problems in multi-hop wireless network caused by the sensing range that is larger than the usually considered transmission range. We may also consider how the networks composed of heterogenous nodes with different transmission radius and life span effect the scatternet formation and may give more consideration on how the different scatternet topology effects packet routing.

References

[1] Bluetooth Special Interest Group, ”Specification of the Bluetooth System”, version 1.0B, *http://www.bluetooth.com*.

[2] T. Salonidis1, P. Bhagwat2, L. Tassiulas1, and R. LaMaire3, Distributed Topology Construction of Bluetooth Personal Area Networks. *INFOCOM 2001. Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE , Volume: 3 , 22-26 April 2001 Page(s): 1577 -1586 vol.3 .*

[3] F.C. Chonng, C.K. Chaing, Bluerings - Bluetooth scatternets with ring structure. *Proc. IASTED Wireless and Optical Communications WOC, Banff, Canada, July 2002.*

[4] I. Stojmenovic, Dominating set based bluetooth scatternet formation with localized maintenance. *Parallel and Distributed Processing Symposium., Proceedings International, IPDPS 2002, Abstracts and CD-ROM , 15-19 April 2002 Page(s): 148 -155 .*

[5] J. Wu and H. Li, On calculating connected dominating set for efficient routing in ad hoc wireless networks. *DIAL M, Aug. 1999,7-14 .*

[6] A.C.C. Yao, On constructing minimum spanning trees in k-dimensional spaces and related problems. *SIAM J. Computing, 11, 1982, 721-736 .*

[7] G. V. Zaruba, S. Basagni, and I. Chlamtac, Bluetrees - Scatternet Formation to Enable Bluetooth-Based Ad Hoc Networks. *ICC 2001, vol.1, pp273-277,* July 2001.

[8] C. Petrioli, S. Basagni, Degree-constrained multihop scatternet formation for Bluetooth Networks *Proc. IEEE GLOBECOM 2002 .*

[9] G.V. Zaruba, S. Basagni, I. Chlamtac, Bluetrees-scatternet formation to enable Bluetooth-based ad hoc networks. *Communications, 2001. ICC 2001. IEEE International Conference on , Volume: 1 , 11-14 June 2001 Page(s): 273 -277 vol.1 .*

[10] M. Sun, C. Chang, T. Lai, A self-routing topology for Bluetooth scatternets. *Parallel Architectures, Algorithms and Networks, 2002. I-SPAN ’02. Proceedings. International Symposium on , 22-24 May 2002 Page(s): 13 -18 .*

[11] Z. Wang, R. J. Thomas, Z. Haas, Bluenet - a New Scatternet Formation Scheme. *Proc. of the 35th Hawaii International Conference on System Sciences - 2002 (CD-ROM).*

[12] Y. Kawamoto, V.W.S. Wong, V.C.M. Leung, A two-phase scatternet formation protocol for bluetooth wireless personal area networks. *Wireless Communications and Networking, 2003. WCNC 2003. 2003 IEEE , Volume: 3 , 16-20 March 2003 Page(s): 1453 -1458 .*

[13] B. Zhen, J. Park, Y. Kim, Scatternet formation of bluetooth ad hoc networks *System Sciences, 2003. Proceedings of the 36th Annual Hawaii International Conference on , 6-9 Jan. 2003 Page(s): 312 -319 .*

[14] IEEE std. 802-11, *IEEE standard for wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification, 1997 .*

[15] Y. Liu, M.J. Lee, T.N. Saadawi, A Bluetooth scatternet-route structure for multihop ad hoc networks. *Selected Areas in Communications, IEEE Journal on , Volume: 21 Issue: 2 , Feb. 2003 Page(s): 229 -239 .*