Using Piconet Avoidance Techniques to Reduce Interference in Bluetooth Networks

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Abstract

This paper presents techniques to avoid the problem of inter-piconet interference in Bluetooth networks. These techniques aim to reduce the number of piconets created in a Bluetooth networking area. The main advantage of having fewer piconets in a Bluetooth network will be the reduction in inter-piconet interference and hence better network performance. These techniques are simulated in software called BT-Scatter, which was created specifically to perform Bluetooth scatternet formation simulations. Simulations were run for various randomly generated topologies and the number of piconets created for each of the topologies was collected. Results show that the number of piconets created for a Bluetooth network topology reduces by using the proposed techniques.

1. Introduction

Bluetooth is a technology of many promises for which many are yet to be fulfilled. This technology came into existence with the motive to replace the cable between any two communicating devices while providing short-range low power wireless communication [1]. It later became an ad hoc wireless networking technology enabling multiple devices to create a demand-based network and talk with one another. A piconet, the smallest network unit, is formed as soon as a connection is established between two Bluetooth devices. The member devices of piconets may become member of other piconets and thus different piconets internetwork with one another, forming a bigger network called a scatternet. In a Bluetooth area, multiple scatternets can exist as there is no such restriction imposed by Bluetooth specification [1].

Each piconet relies on frequency hopping to avoid interference from other piconets as well as non-Bluetooth devices in the 2.4 GHz ISM band. Interference between any two piconets occurs when the transmission frequency of any two piconets coincides or even frequencies are on adjacent band. So inter-piconet interference could be due to either co-channel or adjacent channel interference. Since there are a limited number of frequency hopping bands available,this problem becomes more severe as the number of piconets in a given physical area gets large [2]-[4]. The number of piconets may increase due to either more Bluetooth devices entering into the area or from more interconnection requests among the devices. Zanella et al. [3] proved that interference in piconets depends not only on the number of participating devices but also on the distance between the transmitter and receiver devices. Souissi et al. [4] proved that maximum link reliability with 15 access points (or piconets) is 50% and as the number of access points increases, adjacent channel interference impacts throughput with approximately same severity as co-channel interference. All these findings proved the need to fight interference in Bluetooth networks especially in scatternets where there can be a large number of piconets.

To reduce interference in scatternets, the basic requirement will be to limit the number of piconets without hurting the ad-hoc nature of Bluetooth. Several researchers have proposed to create a tree topology for the participating Bluetooth devices and piconets. However, this approach hurts the ad hoc nature of Bluetooth. To create a network topology that works with reduced interference while preserving the ad hoc nature of the network, the participating devices should be allowed to create connections without any restrictions. This can be achieved by using piconet avoidance techniques that attempt to prevent the creation of new piconets when new connections are established. The work presented here provides a methodology for minimizing the number of piconets present in a truly ad hoc Bluetooth scatternet.

Section II provides the issues in creating Bluetooth networks and introduces the term minimum piconet. Section III provides the techniques to avoid the creation of minimum piconets and thus to reduce the total number of piconets for any Bluetooth network topology. Section IV will explain the simulation software BT-Scatter, the simulation results and a discussion on the results.

2. Piconet growth in Scatternets

The main reason that leads to a large number of piconets in a Bluetooth area is the way two Bluetooth devices connect with each other to form a piconet. As soon as a connection is established between two devices, the device that has initiated the connection will become the master and it will start

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controlling the operation of the link. The other device that has accepted the connection will be the slave and it will get synchronized with the master device. In another perspective, the master is the client device that wants to use the service of the slave that is the server device. The master may also establish links with other devices and bring them under its piconet. A master can accommodate only seven active slaves in a piconet but may have more slaves if some of the slaves agree to be in low power modes [1].

As mentioned earlier, the connection of two or more piconets forms a scatternet. The complexity of a scatternet can be estimated in terms of the number of interconnections among the participating piconets. A device that is common in two piconets provides the interconnection for the piconets. Often called a bridge node, it can be the master in one piconet and the slave in the other, or it can be the slave in both piconets. It may happen that multiple interconnections may exist between two piconets. Although the topology having multiple interconnections may seem complex, it will result in simpler scheduling and routing between those piconets compared to scatternets that rely on inter-piconet scheduling and routing.

Most scatternet formation algorithms are focused on the approach to bring all the Bluetooth devices into one big Scatternet and to make that Scatternet fully connected [5]–[9]. This restricts the Bluetooth nodes to make direct connections with each other, and it also makes nodes rely on other nodes to route their data to their destination nodes. This results in longer delays for multi-hop indirect connections that lead to degraded link performance.

The foundation for this research is the ability to minimize the number of piconets during scatternet formation. While making an inter-piconet connection, the initiator device, that initiates the connection, will be the master and the acceptor device, that accepts the connection, will be the slave. So the interconnection of two piconets may or may not give rise to a new piconet. If the initiator device is already a master in a piconet, then the acceptor device will join the already existing piconet of the initiator and hence no new piconet will be formed. But if the initiator device is not a master then a new piconet will be created with the initiator device as master irrespective of the role of the acceptor device. This piconet will consist of only one master and one slave device. The name "minimum piconet" is proposed for such piconets of size two. However in the abovementioned case, if the acceptor device is a master then it can switch its role with the initiator device in the newly formed piconet. Now the initiator device will become the slave and will join the already existing piconet of the acceptor device. Hence, by doing so, the minimum piconet can be avoided by role switching.

Another possibility when a minimum piconet may be created is that a free device, i.e. a device that doesn't belong to any piconet, may come into Bluetooth area and connects to a device of an existing piconet. In that case the new incoming device will be initiating the connection and hence it will be the master. A new minimum piconet will be created. It may also happen that two free devices connect with each other and will create a minimum piconet. All such possibilities of connections are listed in Table 1. The table also indicates if a minimum piconet is avoidable.

Table 1. Possible connection scenarios and their results

Initiator's role in its piconet	**Acceptor's role in its piconet**	**Connection result**	**Is Minimum piconet avoidable**
Free	Free	Minimum piconet formed.	No
Free	Master	Minimum piconet formed. Can be avoided if both devices switch roles	Yes
Free	Slave	Minimum piconet formed. Simple role switch won't help to avoid piconet.	No
Master	Free	No minimum piconet.	N/A
Master	Master	No minimum piconet.	N/A
Master	Slave	No minimum piconet.	N/A
Slave	Free	Minimum piconet formed. Simple role switch won't help to avoid piconet.	No
Slave	Master	Minimum piconet formed which can be avoided if both devices switch roles	Yes
Slave	Slave	Minimum piconet formed. Simple role switch won't help to avoid piconet.	No

As shown in the table, a minimum piconet is formed whenever the initiator device is either a free device or a slave in its own piconet. A simple role switch can avoid this minimum piconet if the acceptor device is a master in its piconet; otherwise the minimum piconet is unavoidable. If a complex topology without any connection restriction is allowed, it will result in large number of minimum piconets if they are not avoided. It is worthwhile to note that every piconet begins as a minimum piconet, and it will become non-minimum only when any other device joins this piconet.

During the early stages of a Bluetooth network, most of the devices will be free devices and a large number of minimum piconets will be formed. Some devices will later join existing minimum piconets and those piconets will no longer be minimum. All piconets, minimum or non-minimum, may also interconnect with one another forming scatternets. This may again create new minimum piconets. So one can expect minimum piconets to be formed all the time. The number of minimum piconets will keep on increasing with an increasing number of incoming Bluetooth devices and increasing interconnection requests among the piconets.

In a personal networking scenario that involves fewer devices, a complex topology won't hurt and its advantage will be easy and simple networking. In public networking scenarios like an office network or a Bluetooth seminar where the number of devices will be large, the complex topology will be simple and fast to create but the disadvantage will be a large number of piconets in the given Bluetooth area that leads to excessive inter-piconet interference. The use of a complex topology is feasible only when the number of piconets formed can be controlled without imposing any restrictions on the participating Bluetooth devices. In the next section, techniques to avoid the formation of minimum piconets that can be helpful in a public networking scenario will be proposed.

3. Piconet avoidance techniques

The creation of a complex topology having low inter-piconet interference requires the number of minimum piconets to be reduced. Piconet avoidance techniques should be such that minimum piconets are either avoided or absorbed into an existing piconet when they are created. The authors of this paper propose four techniques to avoid minimum piconets. Most of the techniques use the concept of a bridge node, so the bridge node concept and the naming convention to identify a piconet and its member devices will be explained first. Then the piconet avoidance techniques will be given.

When either a free device connects to a non-master member device of a piconet or a non-master member device of a piconet connects to a free device, a minimum piconet will be formed with the initiator device being the master of that piconet. One such case is shown in Figure 1. However if the member device of the piconet is a master, then a minimum piconet will be created only when a free device is initiating the connection. In all cases, the minimum piconet is connected with the non-minimum piconet because both piconets will have a member device as a common device between them. This member device is said to be the bridge node. The bridge node can be used to route traffic between the two piconets.

When a member device of a piconet establishes connection with a member device of a different piconet, a minimum piconet may or may not be formed due to this interconnection. In such types of interconnections, the selection of a bridge node won't be as simple as it was earlier. One such case is shown in Figure 2. Here a bridge node has to be elected between the initiator and the acceptor devices. The method of election will be defined later while explaining one of the piconet avoidance techniques.

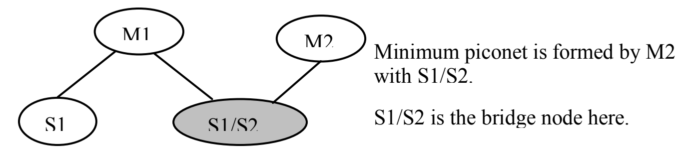

Figure 1. A free device joining an existing piconet

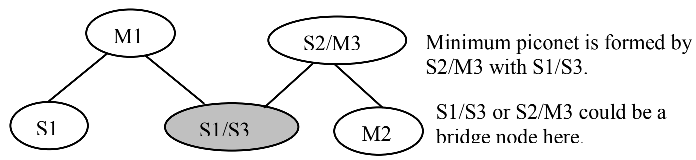

Figure 2. Member devices of two piconets establishing connection

The identifier of each piconet and its slaves will be derived from the identifier of the master. For example, if a master node of a piconet has identifier M1, then the piconet will be called "piconet1", and each of the piconet's slaves will have "S1" as their identifier. If a slave is a member in two piconets, then it will carry two different identifiers due to its roles in each of the piconets. For example, if a device is master M1 and also a slave S2 in piconet2 then its identifier will be M1/S2. Similarly, if a device is slave S1 in piconet1 and slave S2 in piconet2 then its identifier will be S1/S2. It is assumed that general restrictions like the number of connections a node can support, the number of piocnets a node can be a member, and the link quality constraints apply to all these minimum piconet avoidance techniques. All Bluetooth networking restrictions will have priority over these techniques.

3.1. Bridge Node Switch Approach

This approach is based on the following philosophy: "*If a bridge node finds itself being a member of a minimum piconet(s) and it happens to be slave in that minimum piconet(s), then it should switch its role with the master of the minimum piconet(s).*"

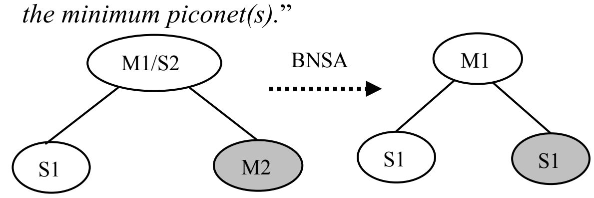

Figure 3. Scenario for BNSA

As shown in Figure 3, bridge node M1/S2 is master M1 in piconet1 with device S1 as a slave. Bridge node M1/S2 is also a member of piconet2 with device M2 as its master. As per BNSA, when the bridge node finds that it has a single device as master in piconet2, then it will switch roles with master M2 and bring it into piconet1 as slave S1. Thus a minimum sized piconet is absorbed here.

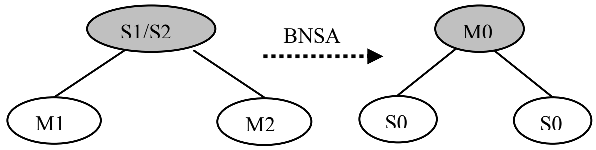

Figure 4. Scenario for BNSA

As shown in Figure 4, two master devices M1 and M2 have established connections with a slave device S1/S2. Both master devices have created two minimum piconets; piconet1 and piconet2. Initially device S1/S2 acts as a bridge node as it is a member of two different piconets. As soon as device S1/S2 knows that there is only one other member in the piconet, then it will ask the master to switch roles with it. In this scenario, device S1/S2 will switch its role with both master devices M1 and M2, and it will create a single piconet with them. So, both of the minimum piconets are combined into one piconet, with the bridge node being master of that piconet.

3.2 Bridge Node Direct Approach

This approach is based on the following philosophy:

"If a bridge node finds a non-minimum piconet on one side and a minimum sized piconet on another side, then it should direct the master of its non-minimum piconet to absorb the other member of its minimum piconet as a slave and provide an indirect connection between them."

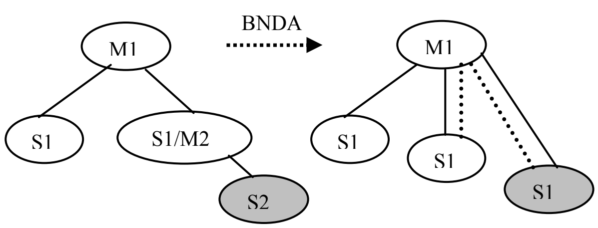

Figure 5. Scenario for BNDA

Bridge node S1/M2 as shown in Figure 5 is a slave member of non-minimum piconet piconet1, and it is the master in a minimum piconet piconet2. The bridge node S1/M2 will direct its master M1 to absorb node S2 as one of its slaves. After absorbing node S2 as its slave, the master node M1 will provide an indirect connection between the nodes S1/M2 (now S1) and S2 (now S1). Many other similar scenarios will be possible where BNDA can be applied.

3.3. Bridge-Bridge Minimization Approach

This approach is based on the following philosophy:

"If there are two prospective bridge nodes in an inter-piconet connection and those nodes are also creating a new minimum piconet together, then a bridge node has to be elected from those two bridge nodes and the elected bridge node will use BNDA to get rid of the newly created minimum piconet."

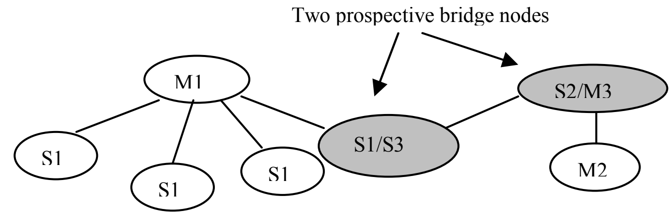

Figure 6. Scenario1 for BBMA

As shown in Figure 6, slave S2 of a piconet2 has connected with slave S1 of piconet1, creating minimum piconet piconet3. Any of the nodes S2/M3 and S1/S3 can be a bridge node for interconnecting piconet1 and piconet2. Such a bridge node should be selected from them so that it would be possible to avoid the creation of minimum piconet piconet3. The selected bridge node will then direct its master to connect with the loser bridge node, and make that node join its piconet. Now the question is which prospective bridge node should be chosen here. One should select the bridge node whose master has a lower weight. The reason behind this selection is that if the master of a bridge node were already being overused, then asking it to accommodate another node would decrease its efficiency. Both prospective bridge nodes will query their masters to report their weights, i.e. the number of connections each master node has. The bridge node whose master has the lower weight will then be the winner of the election and it becomes the bridge node for the interconnection. In the above scenario, S2/M3 wins the election and will direct its master M2 to connect to node S1/S3 and bring S1/S3 under piconet2. After absorbing node S1/S3 as slave S2, the master node M2 will provide an indirect link between S1/S3 (now S1/S2) and S2/M3 (now S2). The resulting topology is shown in Figure 7.

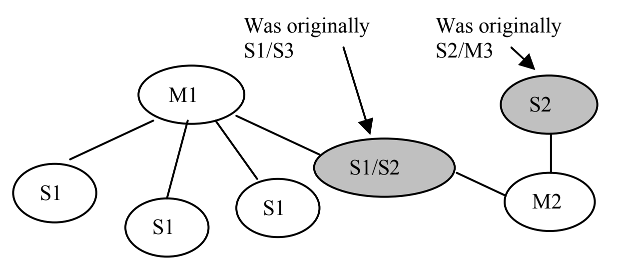

Figure 7. Resulting topology after BBMA for scenario1

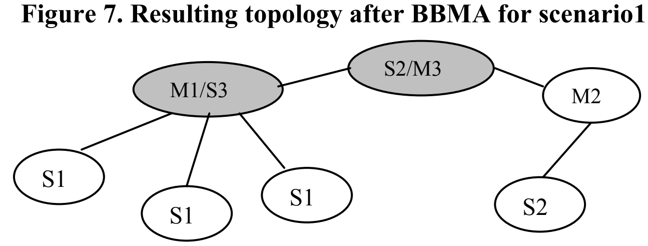

Figure 8. Scenario2 for BBMA

Consider another scenario as shown in Figure 8. In this scenario, slave S2 of piconet2 has created piconet3 with master M1 of piconet1. This connection creates another minimum piconet piconet3 between S2/M3 and M1/S3. Also both nodes M1/S3 and S2/M3 are prospective bridge nodes here. But if node M1/S3 which is also a master becomes a bridge, then a simple role switch with S2/M3 will avoid the minimum piconet piconet3. The resulting topology is shown in Figure 9.

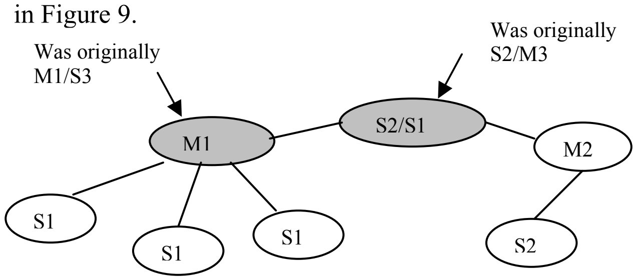

Figure 9. Resulting topology after BBMA for scenario2

In a case when the prospective slave node is a master node and the prospective master is a slave, then there will be no need of election by comparing weights. If any of the prospective bridge nodes is a master, then that bridge node will always ask the other node to switch roles if needed to avoid the minimum piconet. In case both the prospective master and slave nodes have master roles in their piconets, then no election will be needed between them, as there will be no minimum piconet created. No piconet avoidance method needs to be applied here. The following additional statement is needed to define BBMA:

"*If one of the two bridge nodes is a master, then that node will always ask the other bridge node to join it as a slave. If by role switching, a minimum piconet can be avoided and BNSA will be used. If BNSA is not applicable then the bridge nodes should use BNDA*."

3.4. Avoiding Multiple Interconnections Approach

This approach is based on the following philosophy:

"If two slave nodes of a piconet want a direct connection between them, then the master of the piconet should provide an indirect connection between the slave nodes."

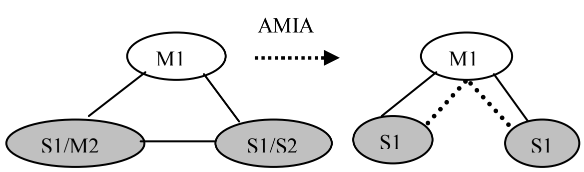

Figure 10. Scenario for AMIA

As shown in Figure 10, the slave nodes of piconet1 have created a minimum piconet, piconet2 with each other. As soon as both slave nodes come to know that they share a common master, they should break the existing connection and should ask the master node M1 to provide an indirect connection between them. This approach is not a new approach and is suggested by the Bluetooth specifications [1].

4. Simulation results

The various proposed piconet avoidance techniques were tested using the software "BT Scatter" developed specifically for scatternet formation simulations. BT Scatter creates a random topology based on the following user supplied parameters:

- number of participating nodes
- number of master nodes creating minimum piconets
- number of master nodes creating non-minimum piconets
- number of interconnections to happen to reach the final topology.

First an initial random topology is created based on first three parameters and all Bluetooth piconet constraints are applied [1]. Once the initial topology is created, then depending upon the number of interconnections, devices to connect or piconets to interconnect are selected randomly. All the mentioned piconet avoidance techniques are applied to avoid formation of any minimum piconet and thus the piconets start to interconnect. To get the complete picture of the performance of piconet avoidance techniques, one of the input parameters is varied while the remaining three parameters are kept constant.

For the cases of increasing number of interconnections, the initial topology will always result in approximately the same number of piconets because the parameters, "number of master nodes having non-minimum piconets" and "number of master nodes having minimum piconets" was kept constant. As the number of interconnections is varied, there will be more opportunities for the existing piconets to connect with each other. Therefore one may expect more minimum piconets to be created out of these interconnections. Since the piconet avoidance techniques are used here so minimum piconets are avoided whenever they are created and so there won't be a rise in the minimum number of piconets. Also, the more is number of interconnections, more minimum piocnets will get chance to combine with other piconets and become non-minimum piconets. One should expect to see a decrease in minimum piconets for the final topology. Similar type of reasoning can be applied to the cases when the number of master nodes creating minimum piconet and the number of master nodes creating non-minimum piconets are varied. Varying the number of participating nodes results in same initial and final topology as the other three parameters that decide the topology are kept constant. So this case is not plotted. The graphs resulting for all the mentioned cases are as follows:

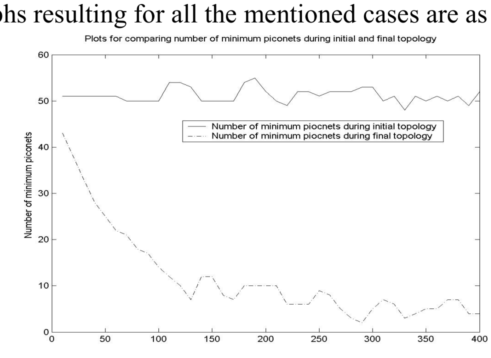

Figure 11. Varying the number of interconnections

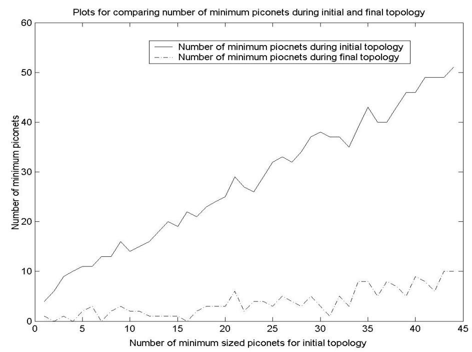

Figure 12. Varying the number of minimum piconets

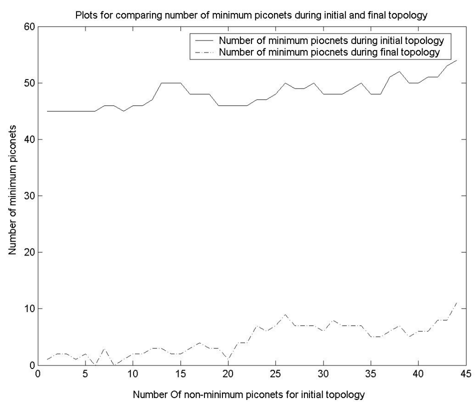

Figure 13. Varying the number of non-minimum piconets

5. Conclusions

Main challenge in Bluetooth networking is to keep the network formation ad hoc and independent. Such a network topology for a large public network will be fast and easy to create but may also result in large number of minimum piconets, which further leads to large inter-piconet interference. The number of minimum piconets can be controlled by using the proposed piconet avoidance techniques. There may be situations (like a small personal network) where minimizing a piconet brings down the throughput or coverage area for the participating nodes, these techniques should be used as optional. Various simulations have been run to show that the number of piconets is drastically reduced using these techniques. Therefore, the performance of the modified scatternet formation should be substantially better than the original one. Integrating the proposed techniques into the existing Bluetooth protocol stack is the next step to further this research. Later, the effect of these techniques on network performance parameters should also be studied and the techniques should be modified if required.

6. References

[1] "Specifications of the Bluetooth system," *http://www.bluetooth.com/pdf/Bluetooth_11_Specifications_Book.pdf* ; Bluetooth Special Interest Group document, February 2001.

[2] Amre El-Hoydi, J.D. Decotignie, "Soft Deadline Bounds for Two-Way transactions in Bluetooth piconets under co-channel interference", in Emerging Technologies and Factory Automation, 2001. in proceedings. 8th IEEE International Conference, 2001.

[3] Andrea Zanella, Andrea Tonello and Silvano Pupolin, "On the impact of Fading and Inter-piconet Interference on Bluetooth Performance" in the 5th international symposium on Wireless Personal Multimedia Communication, WPMC'2002.

[4] Slim Souissi and Eric F. Meihofer, "Performance Evaluation of a Bluetooth Network in the Presence of Adjacent and Co-Channel Interference", IEEE Emerging Technologies Symposium on Broadband Wireless Internet Access 2000.

[5] Theodoros Salondis, Pravin Bhagwat, Leandros Tassiulas and Richard LaMaire." Distributed topology construction of Bluetooth personal area networks," in proceedings of the Twentieth Annual Joint Conference of the IEEE Computer and Communication Societies, 2001.

[6] V. Bhatnagar, A. Choudhary and G. Kesidis, "Bluetooth Scatternet Formation Using Proximity Information of an Election Protocol." CSE Department Technical Report, The Pennsylvania State University, University Park, PA, August 2001.

[7] Ching Law, Amar K. Mehta and Kai-Yeung Siu, " Performance of a new Bluetooth scatternet formation protocol" in proceedings of ACM symposium on Mobile Ad Hoc networking and computing (MobiHoc) 2001, Long Beach, California, USA, October 2001.

[8] G. V. Zaruba, S. Basagni and I. Chlamtac, "Bluetrees-Scatternet formation to enable Bluetooth-based ad hoc networks", in Proceedings of IEEE ICC'2001, Amsterdam, The Netherlands, July 2001.

[9] Godfrey Tan, Hari Balakrishnan and John Guttag, "Interconnecting Bluetooth-like Personal Area Networks", in proceeding at Students Oxygen Workshop, MIT Oxygen Alliance, MIT Laboratory for Computer Science and MIT Artificial Intelligence Laboratory 200 Technology Square, Cambridge, MA 02139.