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Evaluation of Tree Scatternet Formation Algorithm for Enhanced Bluetooth Scatternet

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ABSTRACT: This paper presents an empirical evaluation of Tree Scatternet Formation (TSF) algorithm for enhanced Bluetooth Scatternet. Bluetooth devices operate with an operational range of 10m. This shortcoming in range can be overcomed by the formation of a Scatterrnet. A Scatternet is an interconnection of two or more Piconets. A Piconet is a network of Bluetooth devices within a working range. The interconnection of Piconets has to follow particular topologies for it to be efficient and reliable. Several formations topologies are available. This work evaluates the efficiency of TSF as a Scatternet formation. The TSF algorithm for Scatternet formation is split into three (3) phases: device discovery, tree formation, tree maintenance. The device discovery phase attempts to find neighbouring device and form a master-slave relationship between them. This master-slave relationship only defines connectivity of the local Piconet. In the Tree formations phase, devices attempt to combine connectivity of Piconet to form the main Scatternet in a tree structure. The correctness of the theoretical model was investigated by evaluating an empirical model of TSF. The evaluation revealed that as the tree increases in size, (in term of children nodes being added to specific parents nodes) the overhead increased rapidly in term of Scatternet formation time. This was due to an increased link formation delay due to coordinators nodes. The empirical model had a 3 seconds delay more than the Scatternet formation delay time given by the theoretical model results. Result also showed that TSF exhibited good form formation time for about 16-24 devices.

Keywords: Bluetooth, Piconet, Scatternet, Tree Formation, Master-Slave

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INTRODUCTION

Bluetooth wireless technology is a short-range communications system intended to replace the cables connecting portable and/or fixed electronic devices. It is mostly used to connect personal portable devices within a small range, which accounts for the name 'Personal Area Networks' in the context. During typical operation, a physical radio channel is shared by a group of devices that are synchronized to a common clock and frequency-hopping pattern. One device provides the synchronization reference and is known as the master. All other devices are known as slaves. A group of devices synchronized in this fashion form a Piconet (Pete and Junior, 2000; Tan *et. al.*, 2002; Zaruba *et al*, 2001).

Normal Bluetooth range of operation is about 10 m; this is a serious limitation as personal devices are usually portable and exceeding this distance. However, several Piconets can be interconnected to form a larger network called a Scatternet, which will exceed the traditional range limitation and provide enhanced connectivity. This interconnection of Piconets has to follow particular topologies for efficiency, some of which are Tree Scatternet Formation Algorithm (TSF), Mesh Topology Scatternet Formation (MTSF), and Compact Algorithm for Multi-hop Bluetooth Scatternet Formation (CAMBS) (McDermott-Wells, 2004; Yeow Gong 2004, Jenn-Wei and Wei-Shou, 2010). This paper focuses on the Tree Scatternet Formation (TSF) Algorithm, validating

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its correctness by designing empirical models of Scatternets and comparing the Scatternet Formation Delay results with theoretical results already postulated.

RELATED WORKS

Bluetooth devices discover other devices by following a resource intensive process called enquiry, during which the devices cannot perform any communication (Bluetooth Special Interest Group, 2009). On the other hand, devices that want to be discovered perform a more lightweight process called enquiry scanning, during which they can continue to communicate. After the discovery phase, two devices choosing to connect follow a shorter process called paging, after which one device (master) ends up in control of the link to the other device (slave) and the simplest Bluetooth network, a Piconet, is created. Devices may also agree to perform a master-slave role switch. To allow for the creation of a larger network called Scatternet, devices need to participate in more than one Piconet and provide bridging by assuming the composite role of master/slave or slave/slave.

Existing Systems

There are various topologies for interconnecting Piconets to form Scatternets. In the next sub-sections, various topologies for the formation of Scatternet are discussed.

(a) Mesh Topology Scatternet Formation (MTSF)

The Mesh Topology Scatternet Formation (MTSF) algorithm is a protocol that is scalable and can handle node additions and deletions well. MTSF forms a mesh topology with possibly redundant paths using a distributed algorithm that can be fine-tuned by individual nodes. The algorithm has no restrictions on the size of the Scatternet nor does it require all nodes to be within radio range. Bridges are always formed out of slave/slave relays. More so for MTSF, no prior information about the neighbour nodes is required, eliminating the initial topology discovery phase (Sunkavalli and Ramamurthy, 2002; Sun et al 2002; Miorandi *et al*, 2003).

(b) Compact Algorithm for Multi-hop Bluetooth Scatternet Formation (CAMBS)

CAMBS is another method of forming a tree-based Scatternet. The method consists of three stages. In the first stage, devices are set to discover neighbouring devices. Once discovered, the two devices are set in a master-slave relationship of either a Piconet or an existing Piconet. The second stage involves the formation of a tree from the relationship discovered in the first stage. A set of rules is defined to accurately set and join the relationship within the tree. The third stage is the maintenance of the trees. Devices would periodically enter this stage to check connections, and modify the tree if needed. The main concern of this stage is to ensure tree properties are upheld and that disjoint devices are accounted for (Yeow Gong, 2004).

(c) Tree Scatternet Formation (TSF)

Bluetooth-like link technologies are a recent development, and one can only speculate on how they might be used. Broadly speaking, it is believed that there should be two distinct ways in which Bluetooth-based Scatternets would be used. Some environments, for example, a network connecting household appliances, will be largely static. In these environments, it would be reasonable to statically configure Scatternets in the way many wired (and wireless) networks are configured. TSF aims at more dynamic environments, in which relatively frequent arrival and departure of nodes and node mobility make manual configuration problematic (Tan, 2002). In some dynamic environments, such as in a scheduled meeting, most nodes arrive *en masse*. In other environments, such as in a shopping mall, nodes arrive and leave in incremental fashion. TSF algorithm was designed to work well in both of these dynamic modes. TSF algorithm has the following desirable properties that enhance its operation: (Basagni *et al.*, 2003; Dong and Wu, 2003; Petrioli *et al.*, 2003)

i. **Connectivity**: TSF constantly attempts to converge to a steady state in which all nodes can reach each other. At any time, the topology produced by TSF is a collection of one or more rooted spanning trees, which are each autonomously attempting to merge and converge to a topology with a smaller number of trees.

ii. **Healing**: TSF handles nodes arriving incrementally or *en masse*, and nodes departing incrementally or en masse, avoiding loops and healing network partitions.

iii. **Communications efficiency**: TSF produces topologies where the average node-node path length is small (logarithmic in the number of nodes, avoiding long chains). TSF uses a randomized protocol to balance the time spent by nodes already in the Scatternet between communicating data and performing the social task of forming a more connected Scatternet.

SYSTEM DESIGN

The TSF topology is a collection of one or more rooted spanning trees which were autonomously merged and converged to a topology with a smaller number of trees. This is the underlying design principle which must be adhered to during design.

Design Requirements

The requirements for setting up the Scatternet experiment were simply a collection of between 5-7 Bluetooth devices, which were made up two Piconets that formed the Scatternet. The Scatternet was formed following the Tree Scatternet Formation topology that allowed for both en-masse arrival of nodes or growing nodes in the already existing connection. Standard Bluetooth range is about 10 m, since the objective was to 'increase' this range through the use of a Scatternet; a wider range was needed for the implementation (about 20 m). The Scatternet could be scaled to cater for three Piconets with more Bluetooth devices.

Piconet Design

A Piconet was initialized with two Bluetooth enabled devices, such as a headset and mobile phone. A 3-bit address space limits the number of devices in any Piconet to eight. All devices in a Piconet are peer units and have identical implementations. When establishing a Piconet, however, one device must act as a master for synchronization purposes - the master is dynamically elected when a link is created. The other Piconet units will act as slaves for the duration of the network. Figure 1 showed the design of a five-node Piconet. The Piconet has one master and four slaves. The devices in this Piconet were all within the Bluetooth range of 10 m. The master unit was responsible for synchronizing all other devices in the Piconet. Its clock and hopping sequence were used to perform synchronization. The other three notebooks and two mobile phones made up the slaves of the Piconet.

Scatternet Design

Scatternets are formed from a variety of point-to-point or point-to-multipoint Piconets.

i. Point-to-point Scatternet

In point-to-point connections, there are only two devices, where one is the master while the other is the slave in the Piconet. When one of the nodes in a Piconet elects to become a slave in an adjoining or neighbouring Piconet, a Scatternet is formed. Again, this can apply to both point-to-point and point-to-multipoint connections. The system design for a Scatternet formed from two point-to-point Piconets is shown in Figure 2.

ii. Point-to-Multipoint Scatternets

The design in Figure 3 is the design for a Bluetooth Scatternet across two overlapping Piconets. Each unit has a Piconet of its own with a Master and two or three slaves. The Piconets were connected to adjoining Piconets via a node acting as a bridge.

iii. TSF Protocol design

Tree Scatternet Formation is an algorithm for connecting nodes in a tree like hierarchical structure to form a Scatternet. The TSF algorithm for Scatternet formation is split into three phases: Device Discovery, Tree Formation and Tree Maintenance.

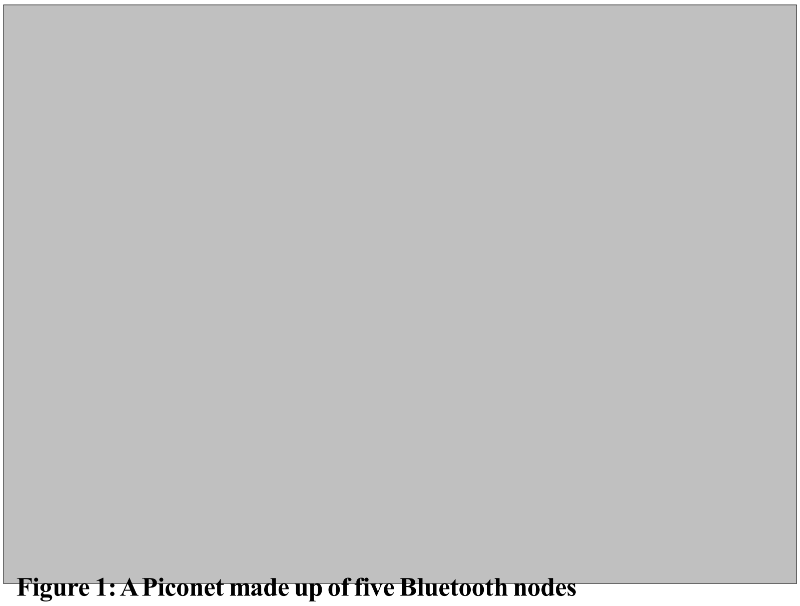

Figure 1: A Piconet made up of five Bluetooth nodes

Figure 2: A Scatternet formed from 2 point-to-point Piconets

Figure 3: A Scatternet of about 25 m range formed from 2 point-to-multipoint Piconets

The Device Discovery phase attempts to find neighbouring devices and form a master-slave relationship between them. This master-slave relationship only defines connectivity of the local Piconets. In Tree Formation phase, devices attempt to combine connectivity of Piconets to form the main Scatternet in a tree structure. Devices are split into root, non-root, or free nodes. Every tree only has one root node, which resides at the top of the tree. Non-root nodes reside elsewhere on the tree, and have exactly one parent. Free nodes are nodes that do not belong to any tree, having no parents and no children.

Figure 4 showed the TSF design of a Scatternet using eight (8) Bluetooth enabled devices. The pocket computer labeled node 0 is the root node while node 1, node 2 and node 3 were its children and at the same time, these nodes were the parent nodes of nodes 7, 5, 6 and 4 respectively. This simple design adequately replicated the Tree Scatternet Formation protocol being considered. Tree Formation Phase attempts to form the parent-child relationships needed for a tree structure. The Tree Maintenance phase maintains the tree structure to account for changes due to node mobility or node failure. TSF requires the use of specific coordinator nodes to perform Tree Maintenance. This leads to high amounts of Tree Maintenance packets, which increases the overall overhead.

Figure 4: Scatternet design using the TSF protocol

During the course of the design, it was observed that as the tree increases in size (in terms of children nodes being added to specific parent nodes), the overhead increased dramatically in terms of Scatternet Formation time. This was due to an increased link formation delay to coordinator nodes.

Topology Maintenance

As the mobility of Bluetooth devices increases, some nodes lose all of their connections and become isolated from the rest of the network. There should be a mechanism for maintaining network connectivity, by rejoining isolated nodes and healing network partitioning. Enhanced personal area networks should enable the reconnection of free nodes that have left the Bluetooth range of overlapping Piconets. The free node should be able to rejoin the Scatternet through a series of operations. The flowchart in Figure 5 shows the reconnection processes engaged in by an isolated node on losing all of its connections.

SCATTERNET FORMATION DELAY IN TSF

Scatternet Formation delay can be defined as the time from when the formation is initiated until every node is incorporated into the Scatternet. As the number of participating nodes increases, TSF suffers from additional overhead due to the coordination between sub-tree root nodes. Tan (2002) posited that the Scatternet Formation delay (in seconds) for TSF increases with incremental node additions as shown in Table 1. However, empirical results using the same specifications as described gave a slightly different result (+/- 3s) as shown in Table 2. This discrepancy may have been due largely to differences in device discovery time for various devices not considered by Tan (2002). The comparison of the results was presented in a graphical format in Figure 6.

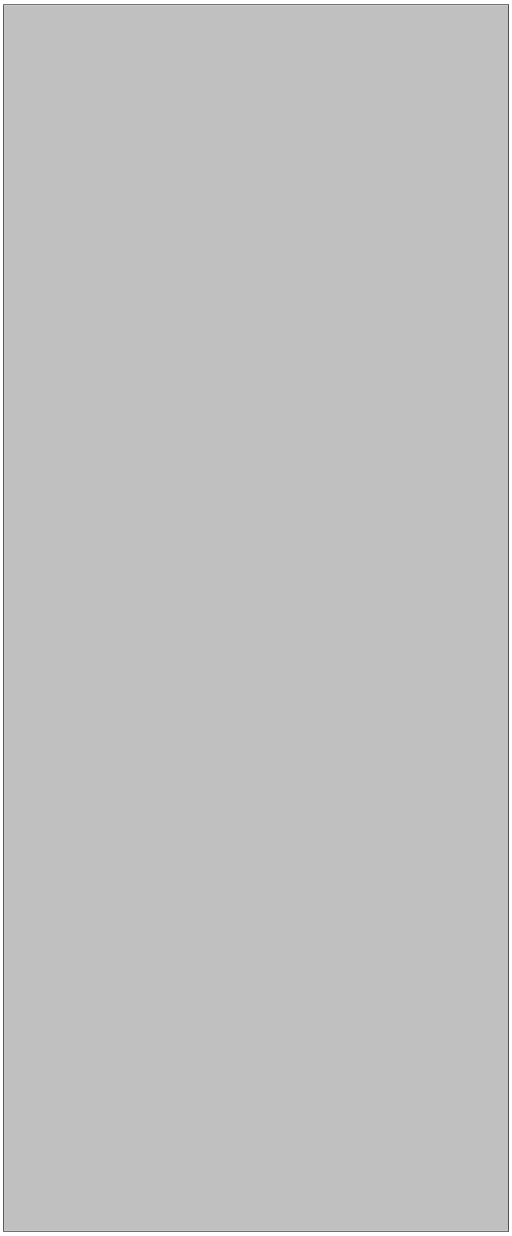

Figure 5: Flowchart showing reconnection processes of an isolated node

Scatternet Formation Delay (TSF) vs. Mesh Topology Scatternet Formation (MTSF) Protocol

MTSF protocol based on McDermott-Wells (2004) was designed and investigated to compare Scatternet Formation Delay times with that obtained from TSF protocol. The results were shown in Figure 7. It was observed that for up to 16 nodes, TSF had a slightly increasing but less Scatternet Formation Delay. However, above 16 nodes, TSF delay increased largely and was higher than MTSF, which showed just the slightest increments for up to 24 and 32 nodes.

Topology Efficiency

TSF protocol demonstrated formation delay efficiency for up to 16 nodes. Considering the fact that a Personal Area Network would most likely not have more than 16 devices; it would be safe to posit that TSF would be the protocol of choice especially in terms of Scatternet Formation time for Personal Area Networks which would not exceed 16 devices and at most 24 devices.

Table 1: Scatternet Formation Delay for increasing nodes (Tan, 2002)

Number of Nodes	Average delay (secs)
4	30
8	32
16	35
24	45
32	65

Table 2: Empirical results for Scatternet Formation Delay of increasing nodes

Number of Nodes	Average delay (secs)
4	33
8	35
16	38
24	46
32	64

Figure 6: Theoretical vs. Empirical results for Scatternet Formation Delay (seconds)

CONCLUSION

In this work, the concept of Scatternet formation was investigated using the TSF algorithm that formed a tree topology. The algorithm is completely distributed and can be dynamically configured. The algorithm is suitable for the formation of Scatternets that span relatively large areas (about 80 m^2) where all the nodes are not within the radio range of each other. Results obtained in Tables 1 and 2 showed that it performs efficiently (less than a minute) when the number of nodes in the network is not more than 24 devices, and achieves an almost constant value in terms of Scatternet formation and new node acceptance delays. Overall, the algorithm has the advantages of tree topology and supports healing after node additions and deletions. The present TSP algorithm provides loop free routing to all Piconets that are at most two hops away from a given master node. This also means that the routing information required is fixed.

Figure 7: Graph showing average delay in seconds for increasing number of nodes for TSF and MTSF

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