

# Dominating set based Bluetooth scatternet formation with localized maintenance

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## Abstract

*This paper addresses the problem of scatternet formation and maintenance for multi-hop Bluetooth based personal area and ad hoc networks with minimal communication overhead. Each node is assumed to know its position and position of all its neighbours. The proposed formation algorithms have three phases. In the first phase the unit graph is constructed (each node establishes connection with all its neighbors that are located within its transmission radius, which is equal for all nodes), and, if planar structure is desirable, localized sparse subgraph (such as relative neighbourhood or Gabriel graph) is extracted. In the second phase, the degree of each node is limited to 7 by applying Yao subgraph construct simultaneously on all nodes with excessive degree, followed by either elimination of directed edges or the application of reverse Yao construct. In the last phase, master-slave relations are created by applying higher degree priority (with dominating set membership as the primary key). The creation and maintenance requires minimal overhead in addition to maintaining accurate location information for one-hop neighbours. The proposed schemes have localized maintenance property (scatternet maintenance due to movement or activity change of a single node is limited to the locality of that node), which is not the case with the existing clustering based Bluetooth scatternet formation schemes.*

## 1. Introduction

The rapid adoption of the internet and mobile and wireless technologies are paving the way for high bandwidth to the mobile terminal. Local and personal area networks are also increasingly becoming wireless, incorporated into seamless all IP wireless and mobile networks. Ad-hoc enabled consumer products will in the beginning be about forming "small-scale" ad-hoc networks between a small group of people/devices. Communication between the nodes in the ad-hoc network can be single hops or multiple hops. Ad-hoc networking in such small networks should offer user friendly and secure network establishment that enables a wide variety of services. One important service is of

course to provide Internet access by interworking ad-hoc networks with already existing infrastructures. Bluetooth is well suited to provide ad-hoc networking for the consumer market. Bluetooth ad-hoc networking presents some technical challenges, such as scheduling issues, network forming and routing. User mobility poses additional challenges for connection rerouting and QoS services. It has been widely predicted that Bluetooth will be the major technology for short range wireless networks and wireless personal area networks. Because of expected low cost of Bluetooth chips, Bluetooth based networks are expected to be the preferred solution to build inexpensive but large ad hoc networks, that is, multi-hop radio networks whose nodes may all be mobile. This paper deals with the problem of building Bluetooth based ad hoc networks.

Bluetooth [H] is an open specification for short-range wireless communication and networking, mainly intended to be a cable replacement between portable and/or fixed electronic devices. According to the standard, when two Bluetooth devices come into each other's communication range, one of them assumes the role of master of the communication and the other becomes the slave. This simple one hop network is called a piconet, and may include more slaves. There is no limit on the maximum number of slaves connected to one master, although the number of active slaves at one time cannot exceed 7. If master has more than 7 slaves, some slaves must be parked. To communicate with a parked slave a master has to unpark it, thus possibly parking another slave instead. The standard also allows multiple roles for the same device. A node can be master in one piconet and a slave in one or more other piconets. The network topology resulting by the connection of piconets is called a scatternet. Bluetooth does not impose limits on the number of roles that a node can assume. The only restriction is that one node can be active only in one piconet. To operate as a member of another piconet, a node has to be able to switch to the hopping frequency sequence of the other piconet. Since each switch causes delay (e.g. scheduling and synchronization time), an efficient scatternet formation protocol can be one that minimizes the roles assigned to the nodes, without losing network connectivity.

While several solutions and commercial products have been introduced for one-hop Bluetooth communication, the problem of scatternet formation has not been dealt with until very recently. Each node should receive master and/or slave roles so that the resulting network is connected. The number of piconets should be minimized to provide faster routing. The formation and maintenance of scatternet should have small communication overhead. In order to minimize the overhead and avoid global scatternet updates caused by node mobility, and changes in activity (that is, local topology changes), we adopt the localized approach in this paper. Localized algorithms are distributed algorithms where simple local node behavior achieves a desired global objective. They therefore resemble the class of greedy algorithms.

A broad variety of location dependent services will become feasible in the near future due to the use of the Global Position System (GPS), which provides location information (latitude, longitude and possibly height) and global timing to mobile users. GPS cards will be deployed in each car and possibly in every user terminal. If GPS is not available, the distance between neighboring nodes can be estimated on the basis of incoming signal strengths. Relative co-ordinates of neighboring nodes can be obtained by exchanging such information between neighbors. In this paper we make use of location information of every node in the network [HB], which is communicated and updated with neighboring nodes only, according to localized approach. Wireless networks are best modeled by unit graphs, where two nodes are connected if and only if the distance between them is at most  $R$ , where  $R$  is the transmission radius, which is equal for all nodes. We adopt unit graph model in this paper, in accordance to almost all research articles on wireless networks.

Bluetooth is a promising new wireless technology, which enables portable devices to form short-range wireless ad hoc networks based on a frequency hopping physical layer. Previous literature on scatternet formation assumed that hosts are not able to communicate unless they have previously discovered each other by synchronizing their frequency hopping patterns. Thus, even if all nodes are within direct communication range of each other, only those nodes, which are synchronized with the transmitter, can hear the transmission. Synchronizing the frequency hopping patterns is apparently a time consuming and pseudo-random process [SBTL]. In this paper we assume that the problem of discovering all neighbors within transmission radius of all neighbors is resolved by separate Bluetooth protocol. We do not believe that Bluetooth technology will dominate the market unless it has such ability. This paper makes such an assumption, and leaves the neighbor discovery problem

as separate issue. There are few feasible approaches in dealing with neighbor discovery process. One solution is to run existing discovery process sufficiently long so that all neighbors are discovered. Speed up can be achieved if nodes cooperate by exchanging locations and identities of discovered neighbors, and their frequency hopping patterns, which can be used for temporary communication or simply in making final decisions. The probability analysis can be used to confirm the practicality of such approaches. The details of such protocol can be elaborated, and are left for future research. Using frequency hopping for neighbor discovery may result in significant delays and inefficiencies (e.g. excessive power consumption) unless an easy basic communication between nodes is provided. An alternative solution may allow all nodes to use a single shared channel (and associated MAC layer protocol such as IEEE 802.11) to exchange their positions with neighboring nodes. Nodes can then make scatternet formation decisions, with little or no additional communication (as will be seen in this paper). Finally, master nodes can simply inform their slaves about frequency hopping pattern to be used in the piconet, and the clock synchronization.

The following section gives literature review on scatternet formation and related network topology design issues. Section 3 gives preliminaries needed to describe our new algorithms. Section 4 presents new Bluetooth formation algorithms based on existing *RNG*, *GG* and *Yao* graphs, and dominating set concept by Wu and Li [WL]. The paper is completed with future work and references.

## 2. Literature review

Zaruba, Basagni and Chlamtac [ZBC] proposed two protocols for forming connected scatternet; the resulting topology is termed a bluetree. The number of roles each node can assume is limited to two or three, thus imposing low slave management overhead. The first protocol is initiated by a single node, called the blueroot, which will be the root of the bluetree. A rooted spanning tree is built as follows. The root will be assigned the role of master. Every one hop neighbor of the root will be its slave. The children of the root will be now assigned an additional master role, and all their neighbors that are not assigned any roles yet will become slaves of these newly created masters. This procedure is repeated recursively till the 'leaves' of the tree are reached (these nodes will only be slaves). Each node is slave for only one master, the one that 'paged' it first. Thus a rooted tree is developed from the root, and each internal node of the tree is a master on one piconet, and slave of another master (except the root). Leaves are slaves only to their parent nodes in the tree.

In order to limit the number of slaves, [ZBC] observed that if a node in unit graph has more than five neighbors, then at least two of them must be connected. This observation is used to reconfigure the tree so that each master  $m$  has no more than  $L > 5$  slaves. If  $m$  has more than  $L$  slaves, it selects its two slaves  $s_1$  and  $s_2$  that are connected and instructs  $s_2$  to be master of  $s_1$ , and then disconnects  $s_2$  from  $m$ . Such branch reorganization is carried throughout the network.

In the second protocol [ZBS], several roots are initially selected (for instance, all nodes that have lower  $id$  than any of its neighbors). Each of them then creates its own scatternet as in the first protocol. In the second phase, sub-tree scatternets are connected into one scatternet spanning the entire network. One of initial roots is selected as the leader. Each sub-tree is treated as the node in a virtual graph, with nodes corresponding to neighboring sub-trees. The first protocol is then run on the virtual graph. A node in resulting scatternet may receive at most one master and two slave roles. Data exchange between sub-trees becomes necessary in order to handle these subtrees as virtual vertices. Although the first algorithm is localized, there is an extensive communication between nodes until the roles are established, and the movement of each node could trigger global update in the subtree rooted by that node and subtree of scatternet the node moved into (that is, maintenance is non-localized). Thus both formation and maintenance of scatternet protocols [ZBC] require considerable communication overhead, which is not measured in [ZBC]. The experiments in [ZBC] measured the difference in hop counts between shortest path routing performed in initial unit graph and bluetree created from it. It also measured average number of initial roots in the second algorithm, that is, average number of nodes with lower  $id$  than any of neighbors.

Distributed topology construction algorithm [SBTL] first collects neighborhood information using an inquiry procedure, where senders search for receivers on randomly chosen frequencies, and detected receivers reply after random backoff delay. Leader is elected in the process, one for each connected component. Leader then collect the information about the whole network, decides the roles for each node, and distributes back the roles. The solution in [SBTL] assumes up to 36 nodes in the network, thus the solution is not scalable, and not localized.

Sparse geometric structures that can be defined locally have been applied in wireless networks for localized routing and broadcasting algorithms. Gabriel graph ( $GG$ ) was used in [BMSU] in order to define planar subgraph used for recovery routing, when simple heuristics fails, to guarantee delivery. Relative neighborhood graphs ( $RNG$ ) were used in [SSS] to

provide efficient localized broadcasting for one-to-one models of wireless communications. Li, Wan, Wang and Frieder [LWWF] proposed to use  $GGs$ ,  $RNGs$ , and  $Yao$  graphs to construct sparse power efficient networks. They also defined *First Gabriel then Yao*, *First Yao then Gabriel*, *Yao and Sink*, and *Yao plus reverse Yao graphs* in order to bound node degrees in network topology, and obtain broadcast trees within a constant factor of the optimum.

There were also attempts to define some sparse structures in distributed manner, but they were not localized. For example, [RM] constructed shortest weighted path routing tree rooted at destination. Hu [Hu] described a distributed, Delaunay triangulation based algorithm for choosing logical links and as a consequence carrying out topology control. However, the construction of Delaunay triangulation is only partially localized, since construction of some edges may require the knowledge of distant node positions.

The feasibility problem of scatternet formation (requiring Bridges to be Slave-Slave) when not all stations are within radio range of each other, has been proven to be NP-Complete [BKNR]. The set of Bluetooth nodes is modeled as a unit graph. A greedy centralized algorithm, where a hypothetical central entity knows the complete topology has been proposed. Distributed algorithms have also been proposed in [BKNR], which assume 2-hop neighbourhood information. This is achievable in Bluetooth since the identities of the neighbouring nodes are known at the end of the device discovery procedure. The nodes are made to exchange this neighbourhood information with each of its neighbours so that they have 2-hop information and a partial view of the underlying topology. The algorithm [BKNR] applies a variant of clustering algorithm with limiting number of nodes in each cluster to seven, in accordance to Bluetooth restriction. A node with highest degree among all its undecided neighbours will become a master node, and will choose up to seven slaves among neighbouring nodes, with priority given to lower degree nodes. However, there are examples where the scatternet is disconnected, which may occur when two clusterheads were originally connected but formed clusters and 'erased' their link without leaving alternate connection between their piconets. For example, assume that the graph contains two connected nodes  $A$  and  $B$ , each with its own seven more neighbours. Thus  $A$  and  $B$  have degrees eight, and will become masters of two piconets, containing their own seven neighbours as slaves. However, the graph will then be disconnected since the link between  $A$  and  $B$  will disappear.

Clearly, the problem is not hard when the underlying topology is a complete graph, i.e., all nodes are within radio range of each other. An algorithm for

Bluetooth scatternet formation in such single-hop networks is recently described by Law, Mehta and Siu [LMS]. However, this problem is also interesting when the Bluetooth communication model is to be used, where limited information has to be exchanged during device discovery. The performance of the device discovery procedures has been investigated in [KRS]. In [RKSA], randomized and deterministic algorithms have been proposed to solve this problem, under the Bluetooth device discovery communication model. We shall briefly describe the deterministic algorithm proposed in [RKSA]. The basic idea of the algorithm is that nodes discovering each other form a tree of responses, the root of each tree being a Master. This process of piconet formation is performed in parallel. Each node  $i$  maintains a 'phase' variable, which is the number of inquiry responses received by it and all the nodes in its subtree. Once a node receives an inquiry response from another node, it increments its phase by the phase of the replying node. A node, which has sent an inquiry response, goes out of the competition for becoming a master. A node whose phase is 8 declares itself master and all the nodes which replied to it and contributed to its phase become its slaves. However, the master node, in this procedure, is not directly connected to all its associated slaves, and the solution is not acceptable for the unit graph model.

Li and Stojmenovic [LS] described a connected degree limited Bluetooth scatternet formation algorithm based on clustering process. Clusterheads then become master nodes, and no two master nodes are directly connected. Two node piconets are added to connect clusters. The problem with clustering approach is that the maintenance of clustered graph structure is expensive, since a local change due to mobility may trigger global change in updating the scatternet. The second phase, degree limitation, in [LS] also applies Yao construct sequentially (node after node, like in clustering), leading to a scheme that does not have localized maintenance property.

This paper will present a Bluetooth scatternet structure with localized maintenance property, based on dominating set concept by Wu and Li [WL]. Dominating sets are sets with the property that each node is either in the set or is neighbor of a node from the set. Localized connected dominating sets were defined in [WL, SSZ] and applied for efficient routing [WL] and for efficient broadcasting [SSS, SSZ].

### 3. Preliminaries

In this section we will define the sparse graphs and dominating sets that will be used in the sequel. Gabriel graph  $GG$  on the set  $S$  of  $n$  given nodes

is defined as follows. Let  $disk(u,v)$  be the open disk with diameter  $(u,v)$ . Then, the Gabriel graph [GS]  $GG(S)$  is a graph in which edge  $(u,v)$  is present if and only if  $disk(u,v)$  contains no other points of  $S$ .  $GG(S)$  is a planar graph (that is, no two edges cross each other). It was proved in [BMSU] that the intersection of connected unit graph and Gabriel graph (defined over the same set of points) is a connected planar graph. It is constructed in localized manner. Let  $A$  be one of nodes, and  $B$  one of its neighbors. Edge  $AB$  belongs to  $GG$  if and only if the (open) disk with diameter  $AB$  does not contain any other node from  $S$ . It suffices to check, for each neighboring node  $C$  of  $A$ , whether  $|CM| < |AB|/2$ , where  $M$  is the center of the circle, that is, the midpoint of  $AB$ . Alternate criterion is the following: an edge  $AB$  is included in the subgraph if and only if  $\angle ACB$  is acute (or is a right angle), for each joint neighbor  $C$  of  $A$  and  $B$ . Therefore, the construction does not require any communication between nodes, in addition to that required to maintain the position of neighboring nodes.

The relative neighborhood graph ( $RNG$ ) is a geometric and graph concept proposed by Toussaint [T]. The definition of  $RNG$  is as follows. An edge  $(u,v)$  exists between vertices  $u$  and  $v$  if the distance between them,  $d(u,v)$ , is less than or equal to the distance between every other vertex  $w$ , and whichever of  $u$  and  $v$  is farther from  $w$ . In other words,  $\forall w \neq u,v: d(u,v) \leq \max(d(u,w), d(v,w))$ . Thus, for an edge  $(u,v)$  to be included, the (open) intersection of two circles centered at  $u$  and  $v$  and with diameter  $uv$  should contain no vertex  $w$  from the set. Both  $GG$  and  $RNG$  graphs are connected and contain minimal spanning tree ( $MST$ ). Their intersection with unit graphs is a connected graph defined in localized manner.  $RNG$  is a subgraph of  $GG$ .

The Yao graph  $YG(k,S)$  [Y] was proposed to construct  $MST$  of a set of points in high dimensions efficiently. For points in a plane, it is defined as follows. At each node  $u$ , any  $k$  equal-separated rays originated at  $u$  define  $k$  cones. In each cone, choose the closest node  $v$  within the transmission range of  $u$ , if there is any, and add a directed link  $uv$  to  $YG(k,S)$ . Ties are broken using any key defined at each node. The reverse Yao graph is defined in the same way, but with all links being reversed, and undirected version of the graph is also occasionally considered.

A set is dominating if all the nodes in  $S$  are either in the set or neighbors of nodes in the set. Nodes that belong to a dominating set will be called internal nodes for  $S$ . Wu and Li [WL] proposed a simple and efficient distributed algorithm for calculating connected dominating sets in ad hoc wireless networks, modeled by arbitrary graphs. They introduced the concept of an intermediate node.  $A$  is an intermediate node if and only if there exist two neighbors of  $A$  that are not direct neighbors themselves. If nodes know the location of all

their neighbors (the assumption made in this paper) then each node can determine whether or not it is an intermediate node without any message exchanged with its neighbors for that purpose. They introduced also two rules that considerably reduce the number of internal nodes in the network, and proved that these rules preserve network connectivity after eliminating additional nodes from the dominating set. Let  $N(u)$  be the (open) set of all neighbors of node  $u$ , and let  $N[u]=N(u) \cup \{u\}$  be the corresponding closed neighbor set, that is the set of all neighbors and  $u$  itself. Suppose that each node has a unique *id* number. Let us define *inter-gateway* and *gateway* nodes as nodes intermediate nodes that are not eliminated by Rule 1, and by Rules 1 and 2, respectively.

Rule 1 [WL] is as follows. Consider two intermediate nodes  $v$  and  $u$ . If  $N[v] \subseteq N[u]$  in  $S$  and  $id(v) < id(u)$ , then node  $v$  is not an inter-gateway node. In other words, if any neighbor of  $v$  is also a neighbor of  $u$ , and  $v$  is connected to  $u$  and has lower *id*, then any path via  $v$  can be replaced by a path via  $u$ , thus node  $v$  is not needed as internal node. We may also say that node  $v$  is 'covered' by node  $u$ . Rule 2 [WL] is defined as follows. Assume that, after applying Rule 1,  $u$  and  $w$  are two inter-gateway neighbors of a inter-gateway node  $v$ . If  $N(v) \subseteq N(u) \cup N(w)$  in  $S$  and  $id(v) = \min \{id(v), id(u), id(w)\}$ , then node  $v$  is declared a non-gateway node. In other words, if each neighbor of  $v$  is a neighbor of  $u$  or  $w$ , where  $u$  and  $w$  are two connected higher *id* neighbors of  $v$ , then  $v$  can be eliminated from the list of gateway nodes.

Stojmenovic, Seddigh and Zunic [SSZ] proposed to replace node *ids* with a record (*degree*,  $x$ ,  $y$ ), where *degree* is the number of neighbors of a node, and  $x$  and  $y$  are its two coordinates in the plane. In Rules 1 and 2, nodes compare first their degrees, and node with higher degree has greater chances of remaining an internal node. In case of ties, use  $x$ -coordinates as secondary and  $y$ -coordinates as ternary keys. The information about the degree of neighboring nodes may be gathered together with information about their location. The experiments presented in [SSZ] indicate that about half of nodes are gateway nodes (more precisely, the ratio falls from 60% for average degree 4 to 45% for average degree 10).

#### 4. New scatternet formation algorithms

We propose several localized scatternet formation algorithms, based on sparse network construction using *RNG*, *GG* and *Yao* subgraphs, and dominating sets.

The first phase in all formation algorithms is the discovery of all neighbors within transmission radius, that is, the construction of the unit graph. This phase

can be also extended to construct a planar subgraph of the unit graph in localized manner. It can be beneficial for routing in the final structure, and also will minimize the overhead of the two remaining phases. The two planar structures considered here are *RNG* and *GG*.

The second phase is applied only at nodes of the unit graph or its *RNG* or *GG* subgraph that have more than 7 neighbors after the first phase. These nodes apply *Yao* structure on them for  $k=7$ , in order to eliminate some neighbors. In [LS], this structure is applied at nodes in sequence, similarly as in clustering process. We propose here to apply *Yao* structure on all nodes with excessive degree simultaneously. Let  $A$  be a node that performs the step in *Yao* structure construction for  $k=7$ . Node  $A$  therefore divides the region into 7 equal angles centered at  $A$ , and chooses one closest node from each region (if any exists), with ties broken using an arbitrary key. We suggest to use (*degree*,  $x$ ,  $y$ ) as the key, with priority given to smaller degree neighbors, so that the roles are divided as evenly as possible. Suppose that  $A$  selected node  $B$  in one of its angular ranges. If  $B$  also selected  $A$  in one of its own angular ranges, the edge  $AB$  is bi-directional; otherwise it remains directed. While out-degree at each node is limited to 7, the in-degree in this step is not, and may result in some nodes serving as slaves in many piconets. To avoid that, we propose to apply one of two constructions, one leading to sparser and other to denser graphs. The sparser structure is obtained by keeping only bi-directional edges, and deleting all directed ones. We will prove that this preserves graph connectivity (the same construct was also considered in [LS], but no proof of its connectivity was given). The resulting structures will be denoted by  $Y$ ,  $YR$  and  $YG$ , referring to *Yao* graph applied on unit graph, *RNG* and *GG* subgraphs of unit graphs, respectively. They are undirected graphs. The other option is to apply the reverse *Yao* construct on all incoming edges at all nodes with excessive in-degrees. That is, only the shortest incoming edge in each angular range is preserved, and others are deleted. The resulting graph is supergraph of the corresponding first, sparser variant, and is therefore also connected. The direction of edges will be ignored (that is, all edges will be declared undirectional), and the resulting graphs will be denoted by  $YY$ ,  $YYR$  and  $YYG$ , respectively, that is, reverse *Yao* graph applied on  $Y$ ,  $YR$  and  $YG$  (before deleting directional edges from them).

**Theorem.** The structures  $Y$ ,  $YR$ ,  $YG$ ,  $YY$ ,  $YYR$  and  $YYG$ , preserve graph connectivity.

**Proof.** Structures  $Y$ ,  $YR$  and  $YG$  consist of bi-directional edges, that is edges selected by both endpoints in the *Yao* construct. Suppose that node  $B_1$  has selected node  $A_1$  in one of its seven regions as the closest node, but node  $A_1$  selected node  $B_2$  in its region

containing  $B_j$ . Therefore  $B_jA_j$  is a deleted edge,  $\angle B_2A_1B_1 < \pi/3$ ,  $B_jA_j \geq A_jB_2$ , and thus  $B_1B_2 < B_jA_j$ . If  $A_jB_2$  is directional edge then similarly there exists  $A_2$  such that  $A_2A_j < A_jB_2$  and  $A_1B_2 \geq B_2A_2$ . Consider the chain of such directed edges  $B_1A_1, A_1B_2, B_2A_2, A_2B_3, B_3A_3, \dots$ . It has the property  $A_{n-1}B_n \geq B_nA_n \geq A_nB_{n+1}$ , due to choices of closest nodes in corresponding ranges. We will show that this chain ends, with the next edge being bi-directional. That is, the sequence of directed edges is finite, and, following the last directed edge  $B_nA_n$ , the next  $A_nB_{n+1}$  is bi-directional. The last directed edge can be indexed alternatively as  $A_{n-1}B_n$ , with edge  $B_nA_n$  being bi-directional, with analogous proof. Assume that, on the contrary, the chain is infinite. Since the set of points is assumed to be finite, the number of choices for nodes  $A_i$  or  $B_j$  is finite (the two sets are not necessarily disjoint). Therefore there exists an edge  $B_nA_n$  (or alternatively  $A_{n-1}B_n$ ) that appears twice in the sequence,  $B_jA_j = B_nA_n$  (more precisely,  $B_j = B_n$  and  $A_j = A_n$ ) for  $j > n$ . Then  $B_nA_n \geq A_nB_{n+1} \geq B_{n+1}A_{n+1} \geq \dots \geq B_jA_j = B_nA_n$ . Therefore  $B_nA_n = A_nB_{n+1} = B_{n+1}A_{n+1} = \dots = B_jA_j = B_nA_n$ . Let  $A_i$  be a node from  $A_n, A_{n+1}, \dots, A_j$  with the smallest key = (degree, x, y). The chain contains edges  $B_iA_i, A_iB_{i+1}, B_{i+1}A_{i+1}$ . This means that node  $B_{i+1}$  selected node  $A_{i+1}$  instead of node  $A_i$  in the corresponding angular range. Since  $B_{i+1}A_{i+1} = B_{i+1}A_i$ , and  $A_i$  has smaller key than  $A_{i+1}$ , this is only possible if  $A_i = A_{i+1}$ . But then the edge  $B_{i+1}A_i$  is bi-directional, which is the fact we wanted to prove.

Suppose that the second step is completed, with some edges like  $AB$  being deleted. Consider now a minimal spanning tree ( $MST$ ) of unit graph,  $GG$  or  $RNG$ , constructed in the following way. Sort all edges  $AB$  according to key (length, survive), where length is edge length, and survive is integer variable with value 0 if  $AB$  is bi-directional after applying Yao structure, value 1 if it is directional, and value 2 if it is not in Yao structure at all. The keys are compared as follows:  $(length1, survive1) < (length2, survive2)$  if  $length1 < length2$  or  $length1 = length2$  and  $survive1 < survive2$ . Ties are broken arbitrarily (more keys are needed for uniqueness, but they are not needed in our analysis). Consider the algorithm that constructs  $MST$  by sorting all edges in increasing order, according to their keys, as defined. Following well-known algorithm, each edge in the sorted order is added to the  $MST$  if its addition does not create a cycle together with previously added edges. Thus among edges of equal length, all bi-directional ones are first considered, then all directional ones, and finally all that are not selected for Yao structure by any of endpoints. Therefore edges of  $Y, YR$  or  $YG$  have priority for inclusion into  $MST$  over other edges of equal lengths.

Consider now an edge  $AB$  of unit graph,  $GG$  or  $RNG$ . If  $AB$  is not selected for Yao structure by any of

two endpoints then there exists node  $C$ , selected by (say)  $A$ , such that  $AC \leq AB$ , and  $BC < AB$ . Both  $AC$  and  $BC$  are considered before  $AB$  for inclusion into  $MST$ . Note that if  $BC$  is not in  $GG$  or  $RNG$  then  $B$  and  $C$  are connected via other edges, all shorter than  $BC$ . Thus  $A$  and  $B$  will be already connected in  $MST$  structure, via other nodes, at the time its  $MST$  membership is to be decided. This is due to the fact that consideration of any edge, such as  $AC$ , for inclusion in  $MST$  makes  $A$  and  $C$  connected, with or without inclusion of  $AC$  into  $MST$ , by the definition (edges are not included to avoid cycles, thus when they are already connected within  $MST$ ).

If edge  $AB$  is directional, say  $BA = B_jA_j$  then there exist a path between them, consisting of shorter edges  $A_1A_2, A_2A_3, \dots, A_{n-1}A_n, A_nB_n, B_nB_{n-1}, \dots, B_2B_1$ , where  $A_nB_n$  is bi-directional edge, whose existence is proven above (again, some of remaining edges may not be in  $GG$  or  $RNG$  but then they are replaced by paths consisting of even shorter edges). All these edges in the path are considered for  $MST$  before  $AB$  is, and therefore  $AB$  is already connected in  $MST$ , without the need for inclusion of it. This means that no directional edge belongs to so constructed  $MST$ . The constructed minimum spanning tree connects all the nodes from the originally connected unit graph,  $RNG$  or  $GG$  and thus the performed second step preserves connectivity.

$YY, YR$  and  $YG$ , are supergraphs of connected graphs  $Y, YR$  and  $YG$ , and are therefore connected. The connectivity of  $YY$  is also proven in [LWWF]. ♦

It remains to determine master and slave roles in structure  $X$  (where  $X$  is one of  $Y, YR, YG, YY, YR$  or  $YYG$ ), which is the third phase in the scatternet formation protocol. We shall describe two such solutions here. The third solution is based on clustering scheme (described in detail in [LS]), and does not have localized maintenance property that is the goal of this paper: local changes may trigger global updates. We shall describe only configurations with *localized maintenance* in this paper, which refers to techniques that limit all configuration changes due a single node movement and changes in activity status to the locality of the node that caused reconfiguration.

The first solution is based on higher degree node being master node, and is also used in a solution from [LS]. Each node creates a key (degree, ID) where degree is again the number of its neighbors in  $X$ , while node coordinates (x,y) can serve as ID. Two neighboring nodes  $A$  and  $B$  compare their keys, and the one with higher key becomes the master node, and the other node is the slave node. Therefore, for each edge of  $X$ , node with higher connectivity becomes master node, and the other node becomes its slave. The purpose of such role is to avoid slave roles at high connectivity nodes. The undirected graph is, in effect,

converted to the directed one, in this third step of formation algorithm. Let us refer to the algorithm that creates such scatternets as  $dX$  (that is,  $dY$ ,  $dYR$ ,  $dYG$ ,  $dYY$ ,  $dYYR$  or  $dYYG$ ).

The second solution (which is the main contribution of this paper), is to apply the dominating concept by Wu and Li [WL]. More precisely, gateway node concept [WL] will be applied on  $X$ . Each node creates a key ( $domin$ ,  $degree$ ,  $ID$ ) where  $domin$  is true if the node is a gateway node, and false otherwise. Nodes belonging to the dominating set have priority in receiving master roles. Between two gateway, or between two non-gateway nodes, the above discussed highest degree criterion is applied. The degree key can be further subdivided as ( $degree$  in  $X$ ,  $degree$  in dominating set of  $X$ ); that is, ties in degrees are resolved by number of gateway neighbors, with  $ID$  applied only if that is also a tie. We will adopt this definition, and will refer to the obtained scatternets as  $gX$  (that is,  $gY$ ,  $gYR$ ,  $gYG$ ,  $gYY$ ,  $gYYR$  or  $gYYG$ ). Note that some variations can also be applied here. For example, each non-gateway node might be assigned to only one master gateway node (for instance, the closest one). Also, piconets between two non-gateway nodes are not needed for connectivity of overall structure.

## 5. Future work

Experiments should compare  $dY$ ,  $dYR$ ,  $dYG$ ,  $dYY$ ,  $dYYR$ ,  $dYYG$ ,  $gY$ ,  $gYR$ ,  $gYG$ ,  $gYY$ ,  $gYYR$  and  $gYYG$  structures in terms of various characteristics, such as average piconet size, average percentage of nodes with various roles:  $S$  (slave only, possibly to few piconets, this can be further divided as  $S^p$ , where  $p$  is number of piconets where slave node serves),  $M$  (master only),  $MS$  (master of one piconet and slave in another), or in general  $MS^p$ , master in one piconet and slave in other  $p$  piconets. Since designed algorithms are the first scatternet formation schemes with localized maintenance property, it is difficult to compare them fairly with structures described in [LS] which do not have such property. In particular, clustering based structure leads to reduced number of piconets as a trade-off for losing localized maintenance property.

The distances between nodes are used as metric in this paper to define localized structures. It is possible to replace it by different metrics, such as minimal power for the communication, delay between nodes, or a bandwidth related metric. The  $RNG$  concept then can be generalized using such metric instead of distances. An edge  $AB$  is not in  $RNG$  only if there exist a node  $C$  such that  $m(AB) > m(AC)$  and  $m(AB) > m(BC)$ . The metric  $m$  may be defined so that all edges receive distinct values (for instance, by using  $id$  of endpoints for breaking ties). All results presented in this paper

and in [LS] are valid if  $m$  is monotone in distance (i.e. if  $x > y$  then  $m(x) > m(y)$ ). Otherwise,  $RNG$  may not be planar, and degree limitation process may disconnect the graph.

The main problem left for future research is the discovery of all neighbors within a transmission radius. This paper assumes that this problem is successfully solved with reasonable time delay (clearly the issue is not in technical feasibility, but in time bounds for achieving this goal). Some results in this direction are given in [MK, KKLYMM]. Two basic approaches are suggested here. The one is based completely on Bluetooth neighbor discovery process with synchronizing frequency-hopping patterns, and exchanging information about discovered neighbors. The other is based on using a single common frequency and IEEE 802.11 medium access protocol in the neighbor discovery process, and switch to frequency hopping after the master-slave relations are established. Each node announces its own location on this channel, or, if the location is not known accurately, uses signal strength and/or signal direction and available information to derive its own location and/or location of its neighbors. The two methods can even be combined. A time slot for location exchange messages can be synchronized, and the frequency of switching to such slot may depend on the overall mobility rate. A simple broadcasting algorithm can achieve synchronization of time slots for this purpose. Other time slots are then used for frequency hopping synchronization. If mobility rate is relatively high, a regular time slot for using common frequency can be maintained. Otherwise, if the mobility is low and network is mostly static, any node that moves can initiate limited broadcasting within local portion of network in order to reserve a common time slot for neighborhood, in which the node can announce its new position to new neighbors. Alternatively, moving node may use existing scatternet network organization to announce its new position to local neighborhood, and initiate scatternet modification. The details of such protocols are left for future development.

The next important problem is to choose the structure that also provides efficient routing on the designed scatternet, in terms of hop count, power consumption, and delay in message delivery (the delay depends on the amount of multiple roles performed by various nodes). Most designed structures are planar and therefore suitable for routing with guaranteed delivery [BMSU], which is an additional benefit of proposed structures. The performance for broadcasting task in Bluetooth scatternet structure can also be considered. Scheduling packets in inter and intra piconet traffic is also a problem that needs further study (e.g. [BCG]).

Other interesting problems arise from the scatternet formation. The protocols in this paper should be enhanced to include the cases when a node enters, moves within or leaves the network, such that the reorganization incurred is minimum. Although localized approach minimizes communication overhead, exact details of Bluetooth protocol need to be described. Another variation could be to consider services assigned by each node and form a scatternet such that inter-piconet communication is minimized.

Finally, the presented algorithms are applicable only when nodes are located in a plane. Scatternet formation for nodes in three-dimensional space (such as devices located on several floors of a building) remains an interesting challenging problem.

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