Static Bluetooth Scatternet Formation Models: The Impact of FHSS

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***Abstract*—The potential of Wireless Personal Network (WPAN) applications is virtually untapped. The presence of low cost Bluetooth technology in most mobile devices makes it the logical choice for further exploration. Existing Bluetooth models neglect its own communication technique, the Frequency-Hopping Spread Spectrum (FHSS), and part of the challenge of generating efficient Scatternet algorithms is related to the characteristics of FHSS. We propose a model of FHSS using dynamic graphs and show the impact of its use in topology of these networks. We show that small changes in a centralized model of Scatternets lead to better traffic and consumption; also, their topology results are comparable to those of dynamic models.**

Keywords*—*bluetooth; scatternet; fhss; dynamic graph.

I. INTRODUCTION

Applications using Wireless Personal Area Network (WPAN) have not yet explored their full potential. The possibility of forming wider-ranging Ad Hoc networks among low cost and low power consumption devices enhances their most common use, which is limited by the data cable replacement. Some of the possible applications of WPAN are: profile, message and location exchange in mobile social networks; mesh networks for Internet access using mobiles as repeaters; networks for monitoring life support medical devices; residential (smart buildings) and industrial automation; dating services and social games, by connecting users with compatible profiles using an open network of mobile devices.

Bluetooth is the most popular WPAN technology [1]: 906 million mobile phones were sold in 2010, almost all with Bluetooth; 171 million laptops were shipped in 2010, 77% of them with Bluetooth; more than 50 million game consoles were shipped in 2010, 62% of them with Bluetooth; more than 40 million Bluetooth enabled health and medical devices were sold in early 2011; one third of all new vehicles produced in 2011 included Bluetooth, which will increase to 70% by 2016.

Studies carried out between 2002 and 2006 [2] introduced different Bluetooth Scatternet formation protocols. Due to the increasing use of Bluetooth, current research has once again focused on the Bluetooth Scatternet formation protocols: [3]–[5], to list a few. However, none of them have been standardized yet and, therefore, no commercial products include this functionality. In the context of mobile social networking applications for example, we found no popular application despite the increasing number of devices manufactured with Bluetooth. This void is due to the complexity of implementing Scatternet algorithms.

Bluetooth allows devices to communicate using channels with a hopping sequence coordinated by the master device and known to all participants in the Piconet. In order to establish a connection, the pattern of frequency hops must be known, a technique called Frequency Hopping Spread Spectrum (FHSS).

The Bluetooth connection process involves two phases: discovery and link formation. During the discovery phase, the device that will assume the role of master scans for slave devices waiting for connection. Master and slaves begin a sequence of pseudo-random frequency hops, until a frequency coincidence occurs. After the match takes place, the link formation phase starts with the slave waiting for a random time to respond to the master: the Backoff interval. Randomness and a Backoff time are necessary to avoid collisions, however, they introduce seconds of delay to the initial connection.

On evaluation of the efficiency of the Scatternet, the FHSS is seen to exert a significant influence on the Bridge nodes, which are responsible for the inter-Piconet communication. In order for a node to act as a Bridge, it must stop communicating within one Piconet and change its standard hopping sequence for another.

During this procedure, the node that plays the role of the Bridge enters into the HOLD state. This procedure has a high associated cost due to the master exchange and subsequently the exhange of hopping sequence and the synchronisation of responses, which are coordinated by the Scheduling. These characteristics mean that the location, volume and types of these Bridges directly influence energy consumption and traffic.

Assessment and understanding of the Scatternet algorithms and models are essential, because many of the delays and losses in performance and energy observed during the formation and coordination were attributed to the complexity of the algorithm that can generate many Bridges, and the need for the discovery of new nodes.

Our study focuses on two issues related to the use of the FHSS in Bluetooth: the randomness of the discovery procedure and the influence of Bridges on the performance of a Scatternet.

We show that there is a substantial degradation of the device discovery procedure, and we analyze how this degradation affects the classic static Bluetooth Scatternet formation. This problem is directly related to the FHSS. According to Jedda et al. [7], [8], this is the main cause of the lack of efficiency in the Bluetooth Scatternet Formation protocols and the absence of its adoption in the standardization process.

Our contribution to this field of research:

- **Model Bluetooth as a Dynamic Graph for use in Static Bluetooth Scatternet Formation Model**: From the work of Pettarin et al. [9], which models Bluetooth as a graph, we improved this model with the *FHS() process* - representing the Frequence Hopping Sequence, and the *Disc()* - representing the Discovery process. These two new functions characterize the Bluetooth graph as a dynamic graph. This model can be used as a requisite to create static Bluetooth Scatternet formation models;
- **A New Optimization Model for Static Scatternet Formation**: We propose an update of a classic static Bluetooth Scatternet formation model, the mathematical programming model described in Marsan et al. [6]. We create a new model by penalizing the activation of Bridges and by including new constraints. This new model produced optimal solutions in which the structure of the Scatternets is more coherent with the ones predicted by Law et al. [10], a well-known dynamic Bluetooth Scatternet Formation model. Our considerations can be used as constraints for other static Bluetooth Scatternet formation models;

Section II shows the related work; Section III-A explores WPANs, detailing the machine in the connection state of Bluetooth. In Section III-B, we model Bluetooth FHSS in a dynamic graph. In Section III-C, we introduce the Scatternet, and in Section III-D, we address the elements that influence the efficiency of its formation. In Section IV, we analyze the effects on FHSS in our experiments. Finally, we detail the conclusions in Section V.

II. RELATED WORK

In Tahir et al. [5] the Scatternet routing protocol (SROP) is proposed. Its main purpose is to establish routes with a minimum number of hops between source and destination. For this to occur, the master searches all possible paths through flooding. Its main advantage is the fact that since the master knows all the links, it can use this information if any device at the source wants to communicate with a member of the Piconet. According to the author, there is a time saving benefit in this search for routes using flooding, and its performance is evaluated in the ns-2 [11] simulator.

Jedda et al. [7] analyzed the impact of Bluetooth specification parameters on the convergence of a Scatternet. These impacts are related to the use of the FHSS communication technique. Using the ns-2 [11] simulator, the differences in convergence times between dynamic and static algorithms in Bluetooth Scatternet Formation (BSF) are shown. Some results showed that changes in the implementation of Bluetooth are more significant in static algorithms.

Pettarin et al. [9] discuss the expansion and diameter of the ad-hoc Bluetooth topology induced by the discovery phase, by means of a Random Geometric Graph (RGG). However, the work does not explore the topology of a Piconet or the intrinsic characteristics of FHSS.

In Law et al. [10] a new dynamic algorithm of Scatternet formation is introduced. In its organization, devices are separated by components. It defines a device, Piconet or Scatternet as a component. They show that their algorithm has $O(\log n)$ time complexity and $O(n)$ message complexity, which generates an algorithm with an efficient battery usage.

In Chiasserini and Marsan [12] the restrictions of the centralized model of Marsan et al. [6] are complemented by a discussion and proposal of distributed algorithms in Scatternet formation, including routines for the insertion and removal of nodes.

Marsan et al. [6] provide a description of the Scatternet formation using mathematical programming. Constraints are proposed in a min-max formulation, leading to an optimization problem, which is solved in a centralized way. However, this article does not take into account the effects of FHSS. This approach is limited to the rules established for each device, without assigning penalties for Bridge nodes.

III. METHODOLOGY

A. WPANs

Wireless Personal Area Networks (WPANs) are wireless networks between low cost, energy-consumption and data-loss devices that create short links around the user's workspace. Bluetooth is the most common WPANs technology, whose communication uses FHSS and has a connection range of 10 m, as found in the most common versions present in the market. FHSS is a common communication technique in ad-hoc peer-to-peer networks. They communicate on one channel for each time slot. They are less susceptible to noise from neighboring networks, can be used at various distances, offer QOS and stronger security compared to traditional 802.11 Wi-Fi. A Bluetooth network is called a Piconet, and its nodes act as master or slaves.

Two distinct phases are required to connect Bluetooth devices: the Discovery and the Link formation. During the Discovery phase, the device that will assume the role of master goes into the INQUIRY state, looking for slave devices awaiting a connection in an INQUIRY SCAN state.

The searching device sends an identifier called Inquiry Access Code (IAC). During the INQUIRY, the IAC is broadcast on 32 of the 79 frequencies defined by the specification, divided into two trains of 16. This sequence of hopping frequencies occurs in a pseudo-random way, with calculations derived from the clock of the device. Master and slaves begin a sequence of pseudo-random frequency hops, until a frequency coincidence occurs.

A time slot difference collaborates with the increased likelihood of the device hearing the same channel on which a IAC was transmitted: the devices in INQUIRY state hop in time slots of $312.5\mu S$ faster than the standard Bluetooth $625\mu S$ used by devices in INQUIRY SCAN.

After receiving an IAC, the slave device assumes a state called INQUIRY RESPONSE, waits for the Backoff time to elapse and responds to the request by sending its network address and clock in a packet called Frequency Hopping Synchronization (FHS). After this process, it enters a state called PAGE SCAN. When the master receives the FHS, it enters a state of PAGE, and uses the information received from the FHS for synchronization and connection with the slave nodes that have already been discovered and are in the PAGE SCAN state.

During Backoff, the device waits for a random value of Time slots $(0 - 639.375)\mu S$. This status is set after the device receives a master's IAC, with the objective of minimizing packet collisions of response to the master. When the Backoff time is over, the device waits for a new IAC in the INQUIRY RESPONSE state, by sending its hop pattern and clock to the master.

During the PAGE state, the master device selects a slave to be connected through its network address, and sends packages through the sequence of estimated hops in the clock of the slave previously discovered.

After the PAGE process is complete, the Piconet is formed and the devices gain an online status and may also negociate the roles of master and slave.

Intra-Piconet communication requires a Scheduling process, during which the master performs a polling on each slave, and only upon receipt of this packet shall they be allowed to communicate again in the Piconet. The order in which the slaves receive this package is called Polling Cycle and it also determines the slots that will be used. This scheduling must be coordinated by an algorithm that determines the sequence in which the master will poll the slaves.

B. Dynamic Graphs

The Bluetooth network will be described as a graph, according to the definition of Gupta and Kumar [13]. According to Pettarin et al. [9], the links can be described by the function $c(n)$, where n is the number of devices, and the range of each device is $r(n)$ With this, the Bluetooth network denoted by the graph $BT(r(n), c(n))$, where $r(n)$ are the vertices V_n and $c(n)$ are the edges E_n. A set of nodes, V_n , with spatial displacement described by a random variable N , uniformly distributed in $[0, 1]^2$; a set of edges E_n , obtained as follows: each vertex, $u \in V_n$, selects a random set of $c(n)$ neighbours, all at the distance of $r(n)$; one edge $e_i = \{u, v\}$, $e_i \in E_n$ exists only if the vertex u selects another vertex v.

Pettarin et al. [9] describes a situation in which the devices are moving and setting the Bluetooth network connection, as a sequence of graphs $G_t(n, \rho, r(n), c(n), t)$, in which ρ is the set of nodes that are part of the connection graph, and t is each time step, linked to the movement of devices. This sequence of graphs can be compared to a Markov chain, whose transition can be described by the model of moving nodes or by spontaneous disconnections.

Assuming that F is the set of frequencies used in FHSS, so that $f_i \in F, 0 < i \leq 79$. FHS is a function of $FHS(CLK, MS)$, where CLK is the clock of the elements involved and MS is the address of the Piconet master. The details of FHS are given by Bluetooth specifications. We have F', so that $f_i = FHS(CLK, MS)$, which is an pseudo-random sequence of the set F. The sequence of F' is unique to each master-slave link. Thus, for communication to take place, each $e_i = \{u, v\}$ must have the same F'.

Let u and v be vertexes that meet the formalization described in the previous section. We define the discovery process as the operation $Disc(u, v, f_i)$, an operation to insert an edge from the set E_n. The $Disc()$ process has its execution distributed, while running u and v at the same time. Master and slaves begin a sequence of pseudo-random frequency hops, until a frequency f_i coincidence occurs. Once matched, the slave waits for a random time to respond $FHS()$ to the master, and this is called the Backoff interval. This is necessary because the $FHS()$ must be exchanged between nodes. For this reason, after $Disc()$ the slave returns $FHS()$ and generates the correct F' for the connection. MS will belong to the element that has been selected as the master.

Given this definition, the graph $BT(r(n), c(n))$ can be classified as a dynamic graph. According to Frigioni et al. [14], a dynamic graph is a graph G whose edges are not fixed and in which some property p of a given graph $G = (V_n, E_n)$ is considered to be true after a series of operations. The algorithm that maintains this property classifies the vertices and edges in different states, with operations that alter these states. These sequences and operations define a dynamic model of edges, which can be removed and inserted into E_n during the verification of F'.

C. Scatternets

Scatternets are collections of Piconets that are formed spontaneously without fixed infrastructure. They are dynamic networks that enable nodes to communicate in scenarios of more than one hop. They break the centralized limits of the *Bluetooth* specification with star topology, coordinated by a master, thus making mesh formations possible. The Scatternet formation rules do not receive further details from the Bluetooth specification, thus enabling other alternatives to be created by means of distributed algorithms, which establish the rules of Piconet associations.

The elements that enable multihop communication across the Scatternet are called "Bridges". They are needed for inter-Piconet communication. They alternate the pattern of frequency hopping among those masters connected. The Bluetooth mode that defines this operation is the HOLD mode. This Bluetooth state is used as a solution for the coexistence of a node in more than one Piconet.

The HOLD mode permits FHSS nodes to be Bridges and to interact with other networks. During the HOLD mode, an exchange of the node's master takes place and hence, a synchronization of the channel with the Piconet must occur. This way, a node leaves its Piconet, changes its hopping pattern, and starts to receive Pollings from the master of another Piconet. It should be noted that a device cannot be the master of more than one network, but may be master in one Piconet and a slave in multiple Piconets, acting as a Bridge. This procedure has a cost associated to the change of hopping pattern from another Piconet and with Scheduling. These costs directly influence the optimization of Scatternet, which in turn, directly influences energy consumption and traffic.

Now we introduce the static and dynamic models.

1) Static Model: The centralized model of Scatternet, also known as the static Bluetooth Scatternet model, is not a protocol. Instead, it provides a description of the Scatternet formation using mathematical programming, and constraints are proposed in a min-max formulation, leading to an optimization problem which is solved in a centralized way. It can find the best possible performance for a given graph, obeying the Piconet Bluetooth restrictions. The objective of this model is to minimize the traffic of nodes that are subject to greater congestion and energy consumption, such as the masters and Bridges, respecting the restrictions following the full convergence of the Scatternet. After that, it can be used to generate a Scatternet formation.

Marsan et al. [6] model, for instance, discuss the centralized Scatternet requirements:

- Network Connectivity: there must be at least one path between two nodes in the network;
- System Complexity: in order to reduce the complexity of the network, the number of Piconets is limited to a fixed value;
- Traffic Demand: the network must support the necessary source-destination connection;
- Roles of the Node: there must be some constraints applied to some nodes, according to the role they play: master or slave.

These requirements and constraints lead to a min-max criterion which is solved using CPLEX [15]. In its model of constraints, the pseudo-randomness of the Discovery phase is not included. The influence of the delays caused by the effort involved in switching channels during traffic between Piconets by a Bridge node in HOLD mode is not addressed either.

2) Dynamic Model: Dynamic models of Scatternets are protocols, and its distributed algorithms use the following heuristic [2]:

- Any device is a member of no more than two Piconets; the number of Piconets is close to the optimal; the lower bound of Piconets is $(n-1)/k$, n being the number of network nodes and k the number of slaves in a Piconet;
- Bridge devices should never be masters. This reduces the load Scheduler of the masters, which will then only consider the intra-Piconet communication;
- The number of Piconets is restricted. This reduces the number of potential inter-Piconet conflicts in the Bridges, but limits the potential of alternative routes;
- There should be as few Piconets as possible. This reduces the number of channels to be used and thus potential interference;
- Piconets should not be connected to more than one Bridge. This minimizes the coordination effort needed for Scheduling;
- A device must participate in as few Piconets as possible. This decreases the amount of inter-Piconet Scheduling in the device.

Law et al. [10] show in their dynamic model that their algorithm has $O(\log n)$ time complexity and $O(n)$ message complexity. However, according to Jedda [8], their dynamic model also does not consider the improvements made to FHSS, which appear in Bluetooth version 1.2.

D. Efficiency In Scatternet Formation

The location of Bridges is critical for the evaluation of the impact of the resulting topology. Given they are responsible for the inter-Piconet communication, they are subjected to more communication overhead and processing than other nodes.

We evaluated the influence of the number of Bridges on a Scatternet and the need of the HOLD mode for data to be exchanged between Piconets. The HOLD mode consumes energy and influences traffic, being one of the states that require the greatest effort in the resynchronization of frequencies in the Piconets, and which participates in and awaits communication polling during the Scheduling process. An efficient Scatternet topology should minimize its use because:

1) Fewer Bridges mean less delays in migration to another Piconet during the transmission of the received data;
2) Fewer masters on the network imply fewer Bridges, and fewer delays in the exchange and resynchronization of the channels of the new Piconet.

IV. RESULTS

We used the UCBT [16], an extension that simulates Bluetooth in ns-2 [11], developed by the University of Cincinnati.

In order to assess the delay in the formation of new Piconets during the Discovery phase, we generated instances with 1 master and $c(n)$ neighbouring devices, which were candidates for the role of slave.

In accordance with Pettarin et al. [9], we observed that as the value of $c(n)$ is increased, so is the likelihood of connection. The rationale for this is that during the Discovery phase, all devices in INQUIRY SCAN perform pseudo-random hops in slower Time Slots than the master until there is a match of frequencies. This behavior shows that, despite the increase in density of devices within the range of the master, the FHSS provides greater resilience to collisions and depletion of the spectrum.

Figure 1 shows the formation of a theoretically maximal Piconet, represented by one master and seven slaves. We observed the proportional increase value of $c(n)$ and the time, until it forms a Piconet with 1 master and 7 slaves. This behaviour is explained by the need for matching the channel in the Discovery phase, the Backoff and Scheduling of intra-Piconet packets.

In order for a new discovery to take place, the master needs to stop the intra-Piconet comunication. While the slaves that have already entered the Piconet change to the HOLD mode, waiting for new pollings from the master before recommunicating. The time cost of this operation grows with the

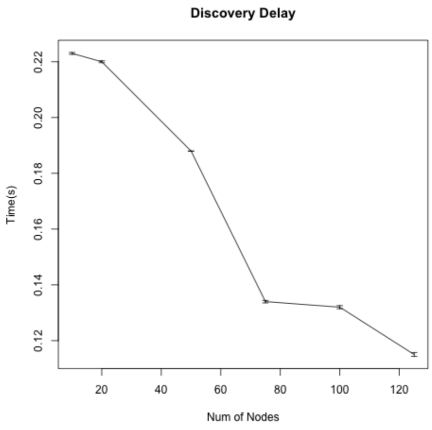

Fig. 1. Time of first master-slave connection

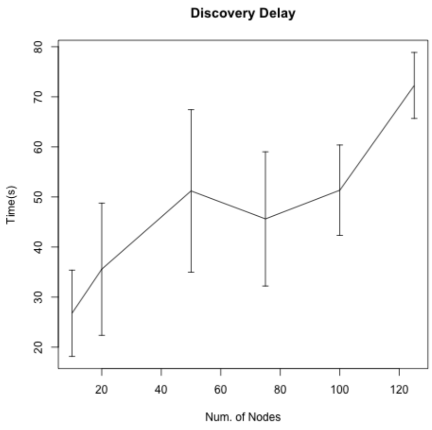

Fig. 2. Time until formation of the first complete Piconet with 7 slaves and 1 master

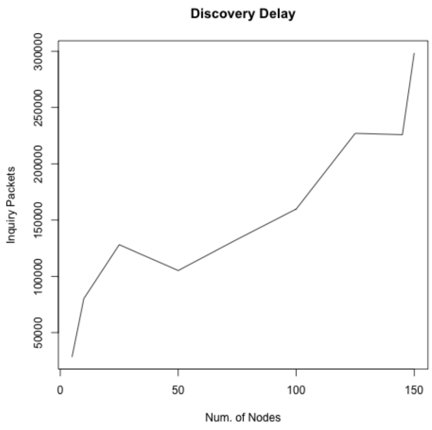

Fig. 3. INQUIRY packets necessary for formation of the first Piconet

increase of devices $c(n)$ due to the randomness of the intra-Piconet Scheduling and Discovery of new slaves. The error bars in Figure 2 show the high degree of variability and delay in connection, represented by random variables associated with the Discovery of slaves, Backoff time and Intra-Piconet Scheduling processes.

Figure 3 shows the number of INQUIRY packets transmitted as a function of the number of devices in the formation of the first Piconet.

A. Topology analysis

To evaluate the efficiency of a Scatternet topology and the influence of Bridges, we simulated the formations with Law et al. [10] algorithms. We generated 30 instances of 20 devices until full convergence. Based on the results, we generated graphs of the most common Scatternet obtained with 20 nodes, Figure 4.

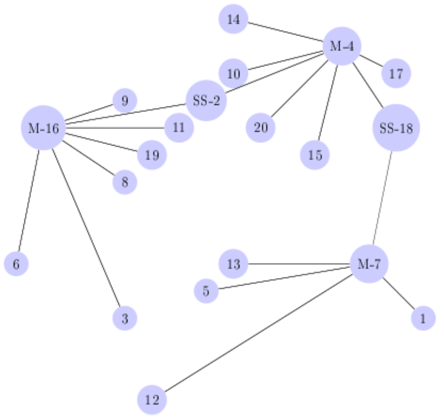

Fig. 4. Common Scatternet of 20 devices found by Law et al. [10] algorithm

The graphs generated in our model follow the rules of efficiency as per the dynamic algorithm of Law et al. [10]; centralized models like Marsan et al. [6] need to be modified so that the results are closer to an efficient energy consumption result.

Looking at the graph shown in the article Marsan et al. [6] Figure 5, we found that some of the items that influence the performance of a Scatternet are neglected:

- The connection between master node 13 with node 0, is a link master / master;
- Node 9 is the Bridge of three Piconets, a prohibitive result;
- We observe various network loops between the Piconets of masters 7 and 17, connected by nodes 9 and 15;
- Four Piconets is an excessive amount for 20 nodes.

B. Improving the centralized model of Marsan et al. [6]

The model from Marsan et al. [6] is described as follows:

- N - Number of nodes;
- C - Connections through network;
- M_{MAX} - Maximum Piconets;
- X_{MAX} - Maximum number of active nodes in Piconet;

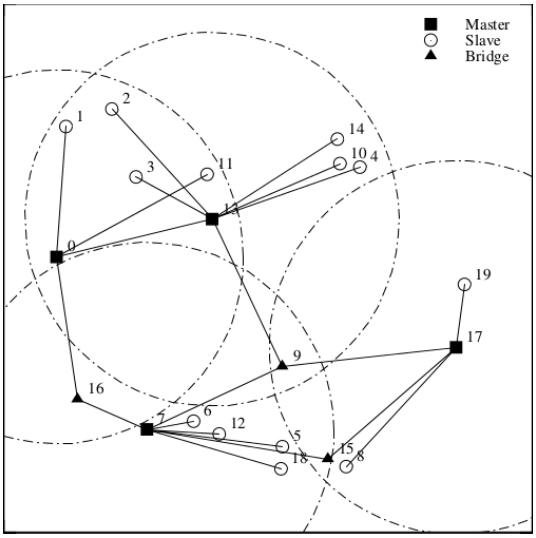

Fig. 5. Scatternet with 20 devices found in Marsan et al. [6] model

- Z_{MAX} - Maximum radius of Piconet.
- M - Nodes constrained to act as masters;
- V - Nodes constrained to act as slaves.

For each node i, $i \in N$, three binary variables are defined: μ_i,β_i, and σ_i, which are equal to 1 if the node is a master, a Bridge or a slave, respectively, and are otherwise equal to 0. For each pair of nodes $(i, j), i, j \in N$, the set $X = \{x_{ij}\}$, x_{ij} is 1 if j is assigned to master i, otherwise 0 .

The model has the following constraints, described in Table I :

$$\mu_i + \beta_i + \sigma_i = 1, \quad \forall i \in N \tag{1}$$

$$\sum_{i \in N} x_{ij} \leq \sigma j + |N|.\beta_j + |N|.\mu_j, \quad \forall j \in N \tag{2}$$

$$\sum_{i \in N} x_{ij} \geq 2 - \sigma j - \mu_j, \quad \forall j \in N \tag{3}$$

$$x_{ii} = \mu_i, \quad \forall i \in N \tag{4}$$

$$x_{ij}.z_{ij} \leq Z_{MAX}.\mu_i, \quad \forall i, j \in N \tag{5}$$

$$\sum_{j \in N} x_{ij} \leq X_{MAX}.\mu_i, \quad \forall i \in N \tag{6}$$

$$2 + x_{ji} \geq \mu_i + \mu_j + x_{ij}, \quad \forall i, j \in N, \quad i \neq j \tag{7}$$

$$x_{ik} + x_{jk} \leq 4 - \mu_i - \mu_j - x_{ij}, \forall i, j, k \in N, i \neq j, j \neq k \tag{8}$$

$$\sum_{i \in N} \mu_i \leq M_{MAX} \tag{9}$$

$$\sum_{i \in M} \mu_i = |M| \tag{10}$$

$$\sum_{i \in V} \sigma_i = |V| \tag{11}$$

In order that the solution to the problem of the centralized model of Marsa et al. [6] generates a topology similar to that obtained by simulation using the dynamic algorithm of Law et al. [10], we had to add two new constraints to the eleven existing in the original model.

TABLE I. MARSAN ET AL. [6] SCATTERNET CONSTRAINTS

Constraint	*Description*
1	a node is either a master, or a slave or a Bridge;
2	a slave is assigned to one master at most;
3	a slave or a master are assigned to one Piconet at least; while a Bridge is assigned to two Piconets at least;
4	a master is assigned to it-self;
5	maximum connect distance is Z_{MAX};
6	limits the size of Piconet to X_{MAX};
7	If nodes i and j are masters; the assignment of i to j if is assigned to i;
8	prevents cycles among sets of three nodes;
9	the maximum number of masters is M_{MAX};
10	nodes in M to be masters;
11	nodes in set V to be slaves.

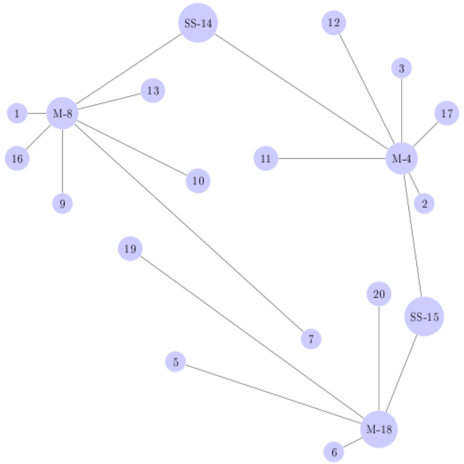

Fig. 6. Scatternet generated with modified model of Marsan et al. [6]

- $\mu_i + \mu_j + x_{i,j} \leq 2 \quad \forall\ i, j \in N \quad i \neq j$ **; a master must only belong to one Piconet.**
- $\beta_i + x_{ij} + x_{ji} + x_{ik} + x_{ki} + x_{kl} + x_{lk} \leq 3 \quad \forall i, j, k, l \in N \quad i \neq j \vee i \neq k \vee i \neq l \vee j < k \vee k < l$ **; a Bridge must only connect two Piconets.**

By adding penalties to the Bridges and these two constraints, we make sure that the resulting graph has a topology that is less prone to effects resulting from delays when Bridges are in HOLD mode. Considering a dynamic graph, these penalties are associated to the cost of functions *Disc()* and *FHS()* shown in Section III-B.

To demonstrate the efficacy of our modification, we used the same instance as that of Marsan et al. [6], with input parameters equal to those of Table II, which form the graph of Figure 5.

TABLE II. INPUT PARAMETERS

N	C	M_{MAX}	X_{MAX}	Z_{MAX}	M	$\|V\|$
20	15	4	8	$\frac{10\sqrt{2}}{3}$	$\{7, 17\}$	0

We can see in the Scatternet topology found by our model in Figure 6, that all the items required for effective formation, as previously mentioned in Section III-D, are respected. Our static model approaches the results of Law et al. [10] as shown in Figure 4. This algorithm has a cost of $O(\log n)$ time complexity and $O(n)$ message complexity, so we can conclude that our resulting graph represents a Scatternet with an ideal distribution of data flow and power consumption.

V. DISCUSSION

The delay of the Bluetooth connection process and the loss of efficiency of some of the algorithms in Scatternet formation are directly related to the effects of FHSS. A correct mapping of its peculiarities is essential for the suitable design of Bluetooth solutions and applications.

The delay in Discovery is the determining factor for simpler applications restricted to a Piconet that requires adequate responsiveness. The *Disc()* and *FHS()* functions in the dynamic graph, shown in Section III-B, models the demand of this factor and its importance in the Scatternet formation. We simulated the formation of Piconets and Bluetooth Scatternets to analyze the delay caused by the discovery process for new nodes during the formation of a new Piconet, and the entry of new slaves into an existing Piconet.

The centralized model that uses mathematical programming is useful in evaluating the performance of the simplest Scatternet topologies. In adapting the classic model of Marsan et al. [6] by changing the weights of the Bridges in the constraints, we achieved results similar to those obtained by simulation of another classic dynamic algorithm.

In addition, we can conclude that our resulting graph of the static Bluetooth Scatternet model represents a Scatternet with an ideal distribution of data flow and power consumption, since its result is similar to that of Law et al. [10]: complexity of $O(\log n)$ time complexity and $O(n)$ message complexity. Our optimization can be used as a requisite for other static Bluetooth Scatternet formation models.

Research that proposes changes to the Bluetooth specification or workarounds for some yet-to-be-explored use examples are a necessity, given the context of the increasing popularity of Bluetooth in Smartphones and Tablets, thereby leveraging this new wave of applications, which is still virtually unexplored due to the side effects of using FHSS.

In future work, we will state that both static and dynamic Bluetooth Scatternet Formation protocols must consider the impact of the FHSS for achieving more practical results and process standardization.

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