A Bluetooth Network Dynamic Graph

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***Abstract*—Bluetooth uses a communication technique called frequency-hopping which has some collateral effects. One of these is a significant delay time during the phase of discovery of nodes. To precisely estimate this delay, we use real and simulated devices, and we measure the elapsed time until a Piconet formation. Our contribution is modeling the Bluetooth network as a dynamic graph, adding the frequency-hopping procedures, Piconet limits and network constraints. These new components render a model which is more consistent with the Bluetooth network technology specification than those presented so far. Our graph can be used as a basis for realistic optimization models.**

Keywords*—*bluetooth; scatternet; frequency hopping; dynamic graph.

I. INTRODUCTION

In 2012, 1.1 billion mobile phones were shipped, almost 100 percent with Bluetooth technology [1]; but, despite this popularity, Bluetooth network applications are not yet explored in their full potential. The new-coming wearable devices, like smart-watches, and smart-glasses to name a few, use Bluetooth intensively. New popular apps, like firechat, also depend on the ad hoc Bluetooth network formation. The possibility of forming wider-ranging ad hoc networks enhances their most common use: files exchange apps and mono headsets.

During communication, Bluetooth devices do not use a fixed frequency; they use frequency-hopping. Therefore, for a link formation, a device discovery phase is firstly needed.

In the device discovery phase, one device scans for another device, and both send and listen messages, respectively, in a pseudo-random frequency sequence, until a frequency coincidence occurs and the synchronization messages are delivered. Even in a smallest network with two nodes, there is a delay time as consequence of the randomness, this prohibits Bluetooth for latency-sensitive applications.

The frequency-hopping sequence and all data flows are coordinated centrally by a node called master, in a master-slave point-to-multipoint network called Piconet. Each Piconet contains only one master, and can have a maximum of seven active slave nodes communicating to $10\,\mathrm{m}$ range.

To expand the limits of this communication, we prefer Scatternets. They are collections of Piconets joined by a Bridge node and coordinated by a protocol.

The collateral effects of frequency-hopping in Bluetooth, such as the delay in discovery phase, show the relevance of a Bluetooth network graph model. It is important to devise a realistic model, having procedures and constraints consistent with the technology specification.

In this work, we have the following contributions:

A Bluetooth network dynamic graph, with:

- The Piconet and Scatternet characterization and topology constraints;
- Master and slaves node rules;
- The proposal, implementation and validation of two procedures: $\mathrm{FHS}()$ and $\mathrm{Disc}()$, which represent a device frequency hopping sequence synchronization and discovery of devices.

These new procedures and network constraints characterize our Bluetooth network graph as a dynamic graph.

In Section II, we describe the initial formation process of a Piconet. Section III discusses the related work. In Section IV the initial connection delay time is identified by simulation and real experiments. In Section V, we present the dynamic Bluetooth network graph model. Finally, the conclusions are in Section VI.

II. PICONET - THE BASIC BLUETOOTH NETWORK FORMATION

In a Piconet, a device assumes the role of master or slave, and two distinct phases are required to connect: the discovery and the link formation.

During the discovery phase, the candidate for the master device goes into the **INQUIRY** state, looking for the devices candidates for the slave in an **INQUIRY SCAN** state.

During the **INQUIRY** state, the searching device sends an IDentifier (ID) by broadcast using 32 of the 79 frequencies defined by Bluetooth specification. The sequence of frequencies that will be used to broadcast ID messages, is a pseudo-random calculate, derived from the clock of the device. The set of this frequencies is called Inquiry Hopping Sequence (IHS).

The candidate for slave device in **INQUIRY SCAN** state listens to broadcasts ID, on the same 32 IHS frequencies, hopping in a pseudo-random sequence derived from its clock.

In this phase, candidates for master and slaves send and listen messages respectively in 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 ID was listened: 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 ID, the candidate for slave device assumes a state called **INQUIRY RESPONSE**, and responds to the request by sending its network address and clock, in a packet called frequency-hopping synchronization (FHS), using the same frequencies of IHS. Then, the device waits for the backoff a random value of time slots $(0 - 639.375)\mu s$, with the objective of minimizing collisions of responses, and goes to **PAGE SCAN** state.

When the candidate for master device receives the FHS, it enters a state of **PAGE**, and uses the information received from the FHS for synchronization and connection with the candidates for slave device that have already been discovered and are in the **PAGE SCAN** state.

During the **PAGE** state, the candidate for master device selects a candidate for slave device to be connected sending packages to the candidate for slave devices previously discovered using the sequence of estimated hops.

After the **PAGE** process is complete, the Piconet is formed and the devices gain a connected status and assume their master and slaves roles.

III. RELATED WORK

Jedda, Jourdan and Zaguia [2] analysed the impacts of changing Bluetooth parameters on the static and dynamic Scatternet formation protocols. These parameters are related to the use of the frequency hop communication technique. The Scatternet formation on static protocols happens as follows; each node alternates randomly between the **INQUIRY** and **INQUIRY SCAN** Bluetooth discovery states, when one device discovers each other, a temporally Piconet is formed until being destroyed at the end of the communication. They called this mechanism of *ALTERNATE*, being examples of it: BlueStars Petrioli, Basagni and Chlamtac [3]; BlueMIS Zaguia, Stojmenovic and Daadaa [4] and BlueNet Wang, Thomas and Haas [5]. In dynamic Scatternet protocols, the discovery phase is interlaced with the network formation, the node shares its time between discovering new devices and communication in the Scatternet. The examples of dynamic protocols are: Law, Mehta and Siu [6] and Cuomo, Melodia and Akyildiz [7]. Jedda, Jourdan and Zaguia [2] using ns-2 [8] simulator, found that changing parameters of Bluetooth 1.2 discovery phase, produce *ALTERNATE* Scatternets 3.5 times faster.

In Pettarin, Pietracaprina and Pucci [9], the Bluetooth dynamic topology was described as a sequence of graphs $\mathcal{G}(n, \rho, r(n), c(n), \epsilon) = \{G_t : t \in \mathbb{N}\}$. Each of the n agents moves to a grid node chosen uniformly at random among the grid nodes within euclidean distance ρ from its current position, being t each time step, linked to the movement of devices. This model describes situations in which the devices are moving and establishing network connections. This sequence of graphs can be modeled as a Markov chain Clementi, Monti, Pasquale e Silvestri [10], whose transitions describe by the model of moving nodes.

Ferraguto, Mambrini, Panconesi and Petrioli [11] proposes a Bluetooth network graph model, where the links can be described by n devices randomly distributed in the unit square, the function $c(n)$ is the neighborhood of each device and $r(n)$ is the range of each device. With this, the Bluetooth network is denoted by the graph $BT(r(n), c(n))$.

Jedda, Jourdan and Zaguia [2] show, by ns-2 simulation, that the parameters changes related to Bluetooth discovery phase, are more significant in static Scatternet protocols, that use use the ALTERNATE strategy, than in dynamic Scatternet protocols as in Law, Mehta and Siu [6]. This opens a discussion about the importance of new propositions that include changes in parameters related to the Bluetooth frequency-hopping.

The Random Geometric Graph (RGG) has been employed for the characterization of Bluetooth network topology. Pettarin, Pietracaprina and Pucci [9] discuss the expansion and diameter of RGG subgraphs induced by device discovery phase. Experimental evidence shows that $BT(r(n), c(n))$ is a ideal model for the Bluetooth topology; see Ferraguto, Mambrini, Panconesi and Petrioli [11]. Unlike our proposed model, classical graph models of Bluetooth as Gupta and Kumar [12], Ferraguto, Mambrini, Panconesi and Petrioli [11], Crescenzi, Nocentini and Pietracaprina [13] and Pettarin, Pietracaprina and Pucci [9], do not explore (i) the topology of a Piconet, (ii) the Scatternet formation, or (iii) the intrinsic influences of frequency-hopping communication.

A correct mapping of frequency-hopping peculiarities is essential for the suitable design of Bluetooth solutions and applications.

IV. IDENTIFYING THE DELAY

In order to measure the elapsed time of a Piconet connection and verify the existence of a connection delay, we generated Piconet instances, using simulation and real devices.

We used the UCBT [14], a ns-2 [8] extension that simulates Bluetooth, developed by the University of Cincinnati. Additionally, to verify the real scenario, we used the Lego NXT Mindstorm [15], and robots were assembled to establish connections with each other via Bluetooth. The Bluetooth communication interface in Lego Mindstorms NXT kits has the channels according with the Bluetooth specification, however the buffer of the equipment does not allow the use of more than three channels simultaneously. Piconets were testes limited to three devices. The robots were assembled as vehicles, and the Bluetooth configured for creating the the communication link as soon as they entered the network range. Once the connection is established, the vehicles should move in opposite directions until losing the communication due to distance. Once the connection between the robots stops, they must return to the starting point to restore the Piconet. Connections were restored even in the presence of thick walls. All the elapsed times were collected while the robots were moving.

In the first experiment, we generated 30 real and simulated instances of Piconets with sizes of two (one master and one slave) and three nodes (one master and two slaves). We measured the amount of time until all the slave nodes were in connected status with the master node. The box-plots in Figure 1 and Figure 2 represent the elapsed time until total connection of nodes in the 30 instances of each Piconet size. We observe that the elapsed time until total Piconet connection is, in mean, one second longer, even between one master-slave link. This is a problem because long connection time is not tolerated by many security and medical applications, among others.

In a second experiment, we generated 30 ns-2 simulation instances to each Piconet formed with one master and n neighboring candidates for the role of slave device. In accordance with Pettarin, Pietracaprina and Pucci [9], we observed that as the value of n increases, 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 frequency-hopping technique provides greater resilience to collisions and depletion of the spectrum. Figure 3 show the elapsed time until first **INQUIRY RESPONSE**.

Figure 4 shows the formation of a theoretically maximal Piconet, represented by one master and seven slaves. We observed the proportional increase value of n and the time. This behaviour is explained by the need for matching the channel in the discovery phase, the backoff and a scheduling of intra-Piconet synchronization packets.

In order to create a new slave entry in an existing Piconet, the master needs to stop the intra-Piconet communication and a new discovery must start. The slaves that have already entered the Piconet change to **HOLD** mode, waiting for new polling from the master before re-communicating. The time cost of this operation grows with the increase of devices due to the new discovery and resynchronization by the intra-Piconet Scheduling process.

The error bars in Figure 4 show the high degree of variability and delay in the connection, represented by random variables associated with the discovery of slaves, backoff time and intra-Piconet scheduling processes.

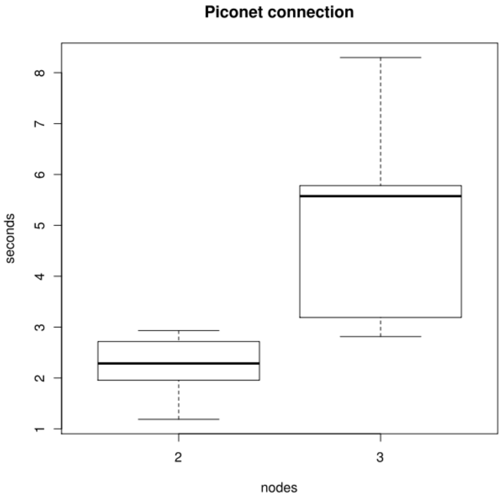

Figure 1. Elapsed Time until complete Piconet connection using Lego NXT.

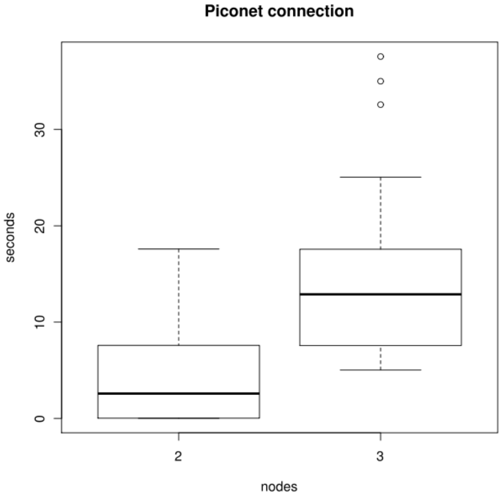

Figure 2. Elapsed Time until complete Piconet connection using ns-2

V. DYNAMIC GRAPH OF BLUETOOTH NETWORK

The Bluetooth network will be described as a graph, following the definition by Gupta and Kumar [12] and Pettarin, Pietracaprina and Pucci [9].

Consider the undirected graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}'\}$ composed by the set of $n \geq 1$ nodes $\mathcal{V} = \{v_1, \ldots, v_n\}$ and of edges $\mathcal{E}' \subset \{\mathcal{V} \times \mathcal{V}\}$, such that $(e_i, e_j) \in \mathcal{E}' \iff (e_j, e_i) \in \mathcal{E}'$. A dynamic Bluetooth graph, able to describe the formation of Piconets and Scatternets, will be defined on top of this generic graph with the inclusion of a spatial restriction and of nodes labels.

A common assumption for the placement of nodes is the fully independent or binomial model Ramos, Guidoni, Nakamura, Boukerche and Frery [16]. According to this model, given n nodes, their coordinates $(x_i, y_i)_{1 \leq i \leq n}$ in the $[0,1]^2$ square are outcomes of $2n$ independent identically distributed uniform $[0,1]$ random variables. Nodes represent devices, and once they are deployed, the links which enable the communication are built according to the range $r(i)$ of each device. The geometric rule says that the edge $(e_i, e_j) \in \mathcal{E}'$ may may exist only if $d(v_i, v_j) \leq \min\{r(i), r(j)\}$, i.e., nodes v_i and v_j may communicate only if both can talk to each other. The distance function $d \colon [0,1]^2 \times [0,1]^2 \to \mathbb{R}_+$ is arbitrary and may incorporate any prior information about the environment as, for instance, obstacles. The choice of the unitary square support does not impair any lack of generality on the model. Many applications assume reciprocal communication setting $r(i) = r$ for every $1 \leq i \leq n$.

The definition of protocols for the operation of Bluetooth networks requires another ingredient: identifying masters and slaves. Each node receives a label, either “M” or “S” for denoting its current state.

A new graph can be now defined, provided the graph $\mathcal{G}$ defined as above. The Bluetooth graph BT is a subset of $\mathcal{G}$

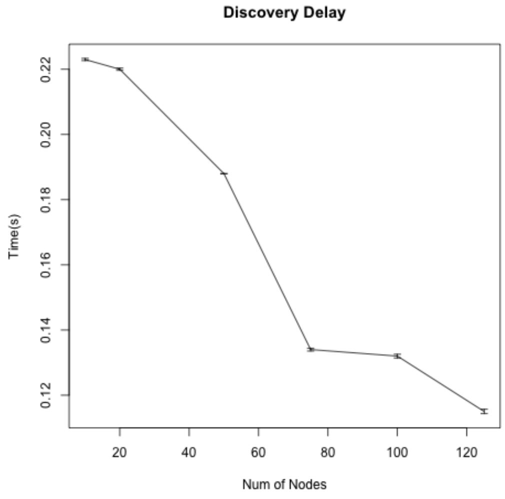

Figure 3. Time until first **INQUIRY RESPONSE**

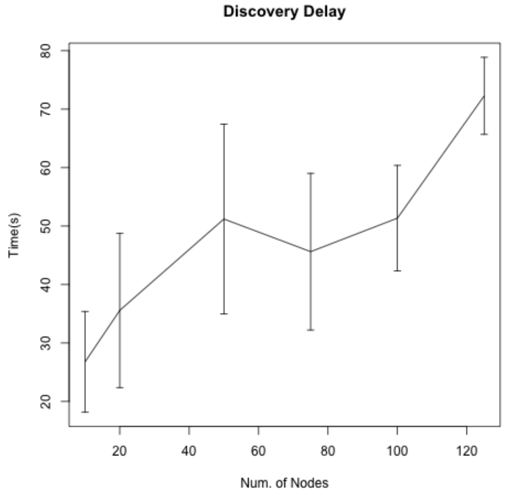

Figure 4. Time until formation of the first complete Piconet with 7 slaves and 1 master

such that $BT = \{\mathcal{V}, \mathcal{E}\}$ since possibly not all allowed connections are set, i.e., $\mathcal{E} \subset \mathcal{E}'$. The communication specification $\mathcal{E}$ has to satisfy the following requirements:

1) There is at least one M node.
2) All S nodes connect to one and only one M node.
3) M nodes do not have connections among them.
4) S nodes do not have connections among them.

A Piconet if formed if there is only one M node and all S nodes connect to it. If there is more than one M node, we are in the presence of a Scatternet.

Pettarin, Pietracaprina and Pucci [9] describe situations in which the devices are moving. The BT graph is, thus, dynamic and can be described as a function of the time $BT(t) = \{\mathcal{V}, \mathcal{E}(t)\}$. The authors describe the sequence of graphs by means of a Markov chain whose transitions express the change of connections due to the movement of the nodes.

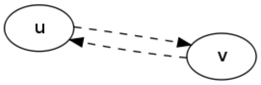

Figure 5. The nodes u and v are in range of each other

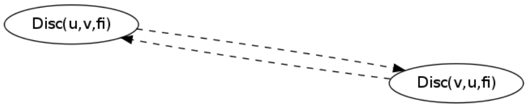

Figure 6. The nodes u and v initialize the discovery $\mathrm{Disc}()$

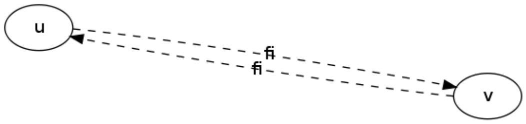

Figure 7. The coincidence of frequency f_i occurs

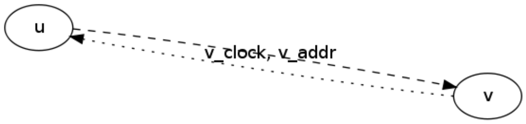

Figure 8. The v node transmit its network address and clock

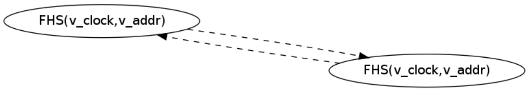

Figure 9. The nodes use FHS() to generate the F' frequency sequence

Denote $F = \{f_i : 0 \leq i \leq 79\}$ the set of frequencies used in FHSS, then FHS is a function $FHS(CLK, MS)$, 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 the Bluetooth specification. Each master-slave link has an unique pseudo-random sequence of frequencies $F' = (f'_1, f'_2, \dots)$, so that $f'_i \in F$.

Let u and v to nodes, as in Figure 5. We define the process of discovery as the operation $\mathrm{Disc}(u, v, f_i)$ which consists of the insertion of the edge (u, v) in $\mathcal{E}$.

The $\mathrm{Disc}()$ process has its execution distributed, while running u and v at the same time, see Figure 6. Master and slaves begin a sequence of pseudo-random frequency hops, until a frequency f_i coincidence occurs, as illustrated in Figure 7. After matching, the slave waits for a random time to respond $FHS()$ to the master, this is called Backoff interval. This is necessary because the $FHS()$ must be exchanged between nodes; see Figures 8 and 9. For this purpose, after $\mathrm{Disc}()$ has been applied, the slave returns $FHS()$ and generates the correct pseudo-random sequence F' for the connection; see Figure 10. The labels “M” and “S” are given to the nodes selected as master and slave, respectively, see Figure 11.

Changes as the ones described above in the connectivity of the Bluetooth network make it a dynamic graph; see Frigioni and Italiano [17].

Figure 10. Now the nodes use the frequency sequence F' to exchange messages

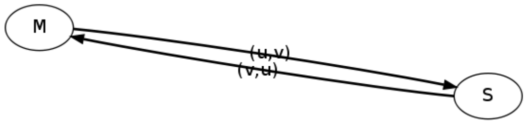

Figure 11. After frequency synchronization, the nodes receive the labels M-master and S-slave, and the links represented by the edges (u, v) and (v, u) begin the message transport

VI. CONCLUSION AND FUTURE WORK

The delay observed during the initial Bluetooth connection process is directly related to the effects of frequency-hopping technology use. This delay is the sum of:

1) in Bluetooth discovery phase:
    - a random value of time until the coincidence of frequencies between listener and sender devices;
    - the random value of time of Backoff until node can listen a response;
2) in Piconet with more than two nodes, during the entry of a new slave in a existing Piconet, a new discovery process is needed, and a intra-Piconet scheduling for master frequency resynchronization.

The randomness in discovery and its collateral effect, the delay, is a crucial constraint for simple Piconet applications that require adequate responsiveness. The $\mathrm{Disc}()$ and $\mathrm{FHS}()$ functions in the dynamic graph, shown in Section V, are the procedures affected.

The problem of delay and specific characteristics of a network using frequency-hopping as Bluetooth Piconet, shows the relevance of a model consistent with the Bluetooth specification as our dynamic graph.

New research proposing changes to the Bluetooth specification need to be leveraged. The search for techniques that reduce the duration of discovery phase, will give rise to new use cases for Bluetooth network.

As future works, we will add the **PAGE** procedures to Bluetooh network dynamic graph, and use it as the basis of the constraints in the Ferreira, Oliveira, Gambini and Frery [18].

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