Towards Feasible Topology Formation Algorithms for Bluetooth-based WPANs

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Abstract

In this paper, we tackle the problem of topology formation in Bluetooth Wireless Personal Area Networks (BT-WPANs). We first overview and extend a previously proposed centralized optimization approach, and discuss its results. Then we outline the main steps of two procedures that can lead to feasible distributed algorithms for the incremental construction of the topology of a BT-WPAN.

The centralized optimization approach has the advantage of producing topologies that minimize the traffic load of the most congested node in the network (thus also minimizing energy consumption) while meeting the constraints on the BT-WPAN structure and capacity. However, the centralized nature and the high complexity of the optimization are a strong limitation of the proposed approach.

Distributed algorithms for the topology formation of BT-WPANs are much more attractive, provided their algorithmic complexity and energy cost are sufficiently low to allow implementation in large BT-WPANs. We discuss distributed procedures for the insertion and the removal of a node in/from a BT-WPAN, which are easily implementable and able to compromise between the system efficiency and its ability to promptly recover from topology changes. These procedures are the key building blocks for a distributed solution approach to the BT-WPAN topology formation problem.

1 Introduction

The Bluetooth technology allows short-range radio devices to communicate in the unlicensed 2.4 GHz ISM band [1]. The basic architectural unit in Bluetooth systems is the *piconet*, composed of a *master* device and at most seven active *slave* devices, which are allowed to communicate with the master only. Overlapping piconets can be interconnected through *bridge* nodes, thus creating a larger network, the so-called *scatternet* or *Bluetooth Wireless Personal Area Network* (BT-WPAN). A Frequency Hopping Spread Spectrum (FHSS) scheme is used at the physical level; each master chooses a different hopping sequence, so that piconets can operate in the same area without significantly interfering with each other. Within each piconet, a TDD technique is employed to transmit and receive data. The radio channel is divided into time slots, which are centrally allocated by the master and alternately used for master and slave transmissions. Because of the use of different hopping sequences, a bridge cannot be active in more than one piconet at a time; thus, bridges have to switch between piconets on a time-division basis, and, while switching, they must re-synchronize with the current piconet. This implies a significant overhead.

The establishment of a link connection between any pair of nodes is performed through the *inquiry* and *paging* procedures. The inquiry protocol enables a node to discover the devices located in its proximity, while the *paging* protocol is used to establish the communication link between two nodes. The device initiating the paging procedure acts as the master of the connection, and the other node as a slave; however, roles can be exchanged later on.

It is clear that master and bridge nodes are subject to a much higher traffic load, relatively to slaves. Also, the performance of a BT-WPAN in terms of throughput and energy efficiency, as well as system complexity, greatly depend on how nodes are grouped into piconets, and which nodes are selected as masters or bridges. Therefore, it is of fundamental importance to develop algorithms for the formation of BT-WPAN topologies, which optimize the performance metrics of interest, while meeting the Bluetooth specifications.

Recently, several schemes for BT-WPANs formation have been proposed [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. The first attempt at addressing the problem of topology formation is presented in [2]. In [3], Miklos *et al.* generate random topologies, and investigate the effect of the topology parameters on the system performance through a simulation study. A scatternet formation algorithm, the so-called

Bluetrees, is proposed in [4]. The Bluetrees scheme forms scatternets with a spanning tree topology, where the parent node is a master and the children nodes are slaves. A network tree structure is also considered in [5]. There, a scheme for the incremental formation of a BT-WPAN is presented, which combines a routing strategy with an address allocation mechanism. A randomized distributed strategy for constructing a BT-WPAN is proposed in [6]; the strategy guarantees that each node belongs to two piconets at most, and that the number of piconets is close to minimal. In [7], a 3-phase algorithm for scatternet formation, named *Bluenet*, is proposed. Bluenet aims at creating a flat network structure and reducing the number of scatternet links, while still maintaining network connectivity. In [9], a BT-WPAN is created as a connected mesh with multiple paths between any pair of nodes to provide fault-tolerance. The algorithm in [9] consists of three phases: neighbors discovery, formation of isolated piconets, and piconets interconnection. The work in [11] tackles the issue of inter-piconet interference, and proposes a construction scheme maximizing the network throughput. However, the scheme assumes that any two nodes are within transmission range. In [12], a ring structure, the so-called *BlueRing*, is proposed in order to provide high reliability and efficient traffic routing and scheduling.

In this paper, we tackle the problem of BT-WPAN topology formation from two different perspectives.

1. We overview an optimization approach originally presented in [10] for the centralized topology formation of BT-WPANs, and discuss the characteristics of the topologies that result from the application of the centralized optimization. The centralized optimization produces topologies that minimize the traffic load of the most congested node in the network while meeting the constraints on the BT-WPAN structure and capacity. Although the centralized nature and the high complexity of the optimization are strong limitations of the proposed approach, the attained solutions provide upper bounds to the performance of any topology derived by means of distributed heuristics. Knowing which are the characteristics of the topologies that optimize the BT-WPAN performance is of critical importance for the development of good feasible distributed algorithms. We investigate the topology performance as the system requirements vary, and evaluate the trade-offs existing between system complexity and network efficiency. In particular, we highlight the fact that increasing the number of piconets that form the BT-WPAN beyond a certain value does not accrue the network throughput, since bridge nodes become the communication *bottlenecks*.

2. We outline the main steps of the procedures that can lead to feasible distributed algorithms for the incremental construction of the topology of a BT-WPAN. The procedures handle the insertion and the removal of a node in/from a BT-WPAN. They are easily implementable, and able to compromise between the system efficiency and its ability to promptly recover from topology changes.

The rest of this paper is organized as follows. Section 2 presents the constraints imposed by the Bluetooth technology and the system requirements that we need to take into account while creating the network topology. Section 3 describes the centralized optimization problem with particular emphasis on the BT-WPAN capacity constraints; some performance results are presented, that show the trade-off existing between system efficiency and complexity. Section 4 introduces the distributed procedures for the incremental formation and the maintenance of a BT-WPAN. Finally, in Section 5 we provide conclusions and discuss some aspects that will be subject of future research.

2 System Constraints and Requirements

The main goal while forming a BT-WPAN should be that the designed topology fulfills the Bluetooth specifications as well as the requirements that may exist on the network structure and throughput.

We summarize the constraints imposed by the Bluetooth technology as follows.

1. **Network structure:**
    - *(a)* The number of active nodes participating in a piconet cannot be greater than 8;
    - *(b)* Two devices have to be within the transmission range of each other in order to communicate;
    - *(c)* A node can be master in one piconet only.

2. **System capacity:** The maximum gross bit rate that can be provided by a piconet is equal to 1 Mbit/s. Hereinafter, we consider the actual piconet capacity, and take its normalized value to be equal to 1. Both constant rate, synchronous connection-oriented (SCO) links, and variable rate, asynchronous connection-less (ACL) links are supported. All SCO links provide bidirectional transmissions with 64 kbit/s in each direction, while the associated capacity depends on the packet type that is employed [13]. A node communicating with a single master can have at most three simultaneous SCO links. When a node is active in two piconets, at most two simultaneous SCO links can be established, because of the time overhead due to switching from one piconet to another. ACL links support

unidirectional data links with ARQ. Their capacity occupation can be easily computed given the model of the traffic source and the average bit rate of the generated data.

The requirements that may exist on the BT-WPAN system are as follows.

1. **Network connectivity.** There must be at least one path between any two nodes in the network. This implies that all masters have to be connected with each other, through either master or bridge nodes; instead, slaves can communicate with any node in the network through the master they are connected to.
2. **System complexity.** In order to keep the network complexity small, the maximum number of formed piconets is limited to a fixed value.
3. **Traffic demand.** The network must support the desired source-destination connections.
4. **Nodes' role**. Constraints on the role that some nodes can have in the network may exist. A node may need to act as either a slave or a master, depending on the application it is able to support, and on its processing capabilities and battery capacity. For instance, nodes that are gateways to the fixed network should be chosen as masters, while earphone devices are likely to act as slaves rather than masters.

3 A Centralized Approach

In this section, we describe a *min-max* optimization problem for the BT-WPAN topology formation. The problem is solved in a centralized manner due to its complexity and the large number of parameters involved. We obtain a topology that meets the constraints and requirements listed in Section 2, while minimizing the traffic load of the most congested node in the network, or equivalently its energy consumption. We present some results that show the network performance as the system requirements vary. Notice that the optimization problem was first presented in [10], but here its formulation is enhanced by adding the constraints on the network capacity. Below we give just a brief overview of the problem formulation; the interested reader can refer to [10] for more details.

3.1 The Min-Max Problem

We consider $\mathcal{N}$ as the set of N stationary nodes, that are randomly scattered in a $Q \times Q$ region. All nodes belong to the same power class[1] and, hence, have a common transmission range. We define $\mathcal{C} = \{(s,d)\ :\ s \text{ is a source and } d \text{ a destination}\}$ as the set of source-destination connections, and C as the total number of connections that have to be routed through the network. We assume that just one route is used for each source-destination pair. For each traffic source s, we take the average traffic rate, denoted by ρ_s, as an input parameter to the problem. As mentioned in Section 2, various link types with different bit rate exist, thus ρ_s will depend on the link type that is considered. Let $T = \{t_{sd}\}$ be the traffic matrix indicating the information rate on each source-destination connection, normalized to the radio link capacity. For each source-destination connection (s,d), we take t_{sd} as a random variable uniformly distributed between 0 and $2\rho_s$, and $2\rho_s$ to be less than or equal to 0.5. Being the normalized piconet capacity equal to 1, this ensures that the traffic generated by a single source can be received and forwarded by intermediate nodes without violating the capacity constraint. We denote by M_{MAX} the maximum number of piconets, and by M and V the number of nodes that are forced to be masters and slaves, respectively.

To formalize the optimization problem, we use three sets of variables: *assignment* variables, *flow* variables, and *routing* variables. For each pair of nodes (i,j), $i,j = 1,\dots N$, we have that:

- an assignment variable is set to 1 if node j is assigned to master i, otherwise it is set to 0;
- a flow variable is set to 1 if there exists any flow from i to j and $i \neq j$, otherwise it is set to 0;
- for each source-destination pair $(s,d) \in \mathcal{C}$, a routing variable is set to 1 if connection (s,d) is routed on arc (i,j), and to 0 otherwise. Notice that the set of variables $\{r_{ij}^{sd}\}$ defines the connection path through the network for any connection in $\mathcal{C}$.

Next, assume that the set of routing variables is given. Then, the traffic load of the generic node i, can be defined as the sum of the incoming and outgoing traffic that i has to handle. We write the load of node i as

$$L_i = \sum_{(s,d)\in\mathcal{C}} L_i^{sd} = \sum_{(s,d)\in\mathcal{C}} t_{sd} \sum_{j\in\mathcal{N}} (r_{ji}^{sd} + r_{ij}^{sd}) \qquad (1)$$

where r_{ji}^{sd} and r_{ij}^{sd} are the routing variables associated with nodes i and j. More specifically, for each connection (s,d), the term $t_{sd}r_{ji}^{sd}$ represents the amount of traffic that node i receives from j, while the term $t_{sd}r_{ij}^{sd}$ is the traffic that i forwards to j, being j the next node in the connection path. We define as the network *bottleneck* the node with the

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[1] The Bluetooth specifications classify devices into three power classes, based on the maximum device output power, namely 100 mW, 2.5 mW and 1 mW. These values of output power correspond to a maximum transmission range of about 100 m, 10 m and 0.1 m, respectively.

highest traffic load, i.e., the node whose traffic load, B, is

$$B = \max_{i \in \mathcal{N}} L_i \,. \tag{2}$$

Our objective is to select the network topology so as to minimize the traffic load of the most congested node, i.e., its energy consumption, while guaranteeing the desired throughput. We denote the optimization problem by $\mathbf{P}$, and write $\mathbf{P}$ as,

$$\mathbf{P} : \quad \min_{\{r_{ij}^{sd}\}} B\left(T, \{r_{ij}^{sd}\}\right)$$

subject to constraints on:

(i) the assignment variables

(ii) the flow variables

(iii) the routing variables. (3)

(i) The constraints on assignment variables ensure that:

- *(a)* each node is assigned a role (master, or slave, or both master and bridge, or both slave and bridge);
- *(b)* a node cannot be assigned to a piconet if its distance from the corresponding master is greater than the piconet radius;
- *(c)* a bridge is assigned to two piconets at least, while other nodes are assigned to one piconet;
- *(d)* the maximum number of nodes assigned to a piconet is equal to 8;
- *(e)* the total number of piconets is less than or equal to $M_{\scriptscriptstyle MAX}$;
- *(f)* the nodes fixed a priori to be masters or slaves are forced to be so.

(ii) In order to guarantee the full connectivity of the network, a graph connecting all the masters in the network must be created. The constraints on the flow variables guarantee that all masters are connected to each other through either master or bridge nodes.

(iii) Given the source-destination connections that the network must support, the constraints on the routing variables ensure that:

- *(a)* for each source-destination pair (s, d), there is a route connecting s to d;
- *(b)* a connection is routed through edge (i, j) only if a link exists between i and j;
- *(c)* a connection is routed through a pair of nodes (i, j), which are masters or bridges, if edge (i, j) belongs to the graph connecting all masters;
- *(d)* loop-free routes are established.

Next, we introduce the constraints on the network capacity, that were not included in [10].

First, we verify that for each piconet (i.e., master) the aggregated traffic does not exceed the piconet capacity. We impose that the traffic load of the bottleneck node is less than the piconet capacity, i.e., $B \le 1$. Such a condition ensures that the traffic load of any node in the network is less than or equal to 1. Since each master handles all the traffic connections within its piconet, this implies that the traffic load of any piconet is less than or equal to the piconet capacity.

Second, for every bridge node we verify that the traffic load plus the overhead due to switching from one piconet to another does not exceed 1. We set the switch overhead to be equal to 2 time slots, i.e., one third of the piconet capacity, and we neglect the delay in starting a master-bridge communication due to the fact that, when the switching takes place, the master may be busy with another transmission. Hence, for every bridge node b, we must have

$$\sum_{(s,d) \in \mathcal{C}} t_{sd} \sum_{i \in \mathcal{N}} (r_{ib}^{sd} + r_{bi}^{sd}) \le 1 - 1/3. \tag{4}$$

In order to derive a feasible BT-WPAN topology, we use the following procedure. We solve problem $\mathbf{P}$ as in (3), and we verify a-posteriori whether the obtained topology fulfills the capacity constraints. This is motivated by the fact that, even if a solution to problem $\mathbf{P}$ does not meet the capacity constraints, it suggests how much we should scale down traffic in order to attain a feasible topology.

Once a feasible solution is found, for any source-destination pair (s, d), we can search for an alternative route if there is any. The method we use is as follows. We fix the assignment and flow variables to the values that they take in the solution of $\mathbf{P}$, while we set to 0 the routing variables (r_{ij}^{sd}) whose value is equal to 1 in the solution. By doing so, we generate a new problem, $\mathbf{P}'$, in which the solution obtained by solving $\mathbf{P}$ is forbidden. If a solution to $\mathbf{P}'$ exists, this provides a new route for (s, d); otherwise, no alternative route for (s, d) can be found.

It can be shown that problem $\mathbf{P}$ is at least as complex as the Geometric Connected Dominating Set problem, which is proven to be NP-complete [14]; hence $\mathbf{P}$ is NP-complete.

3.2 Numerical Results

In [10] we presented results of the centralized topology optimization, showing the traffic load of the bottleneck node as a function of the average sources load and for a fixed value of the maximum number of piconets. We considered that the source-destination connections and their associated rate were known, and that some uncertainty existed in the

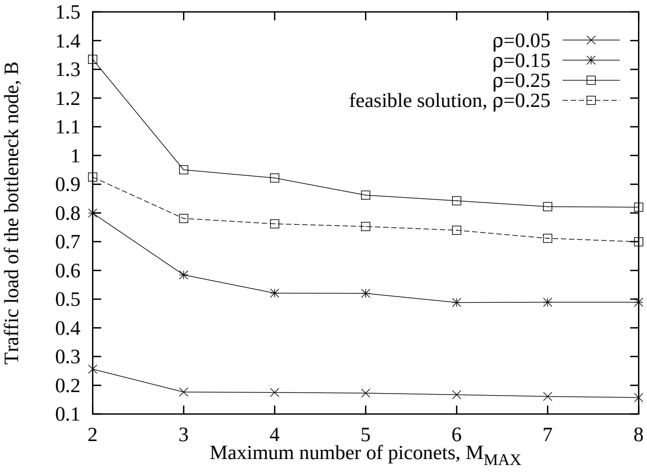

Figure 1. Traffic load of the most congested node in the network as a function of the maximum number of piconets and for $\rho = 0.05, 0.15,$ and 0.25. Results are obtained for $N = 12$, $C = 6$, and by forcing 3 nodes to be slaves. The curve labeled by *feasible solution* is related only to topologies that meet the capacity constraints.

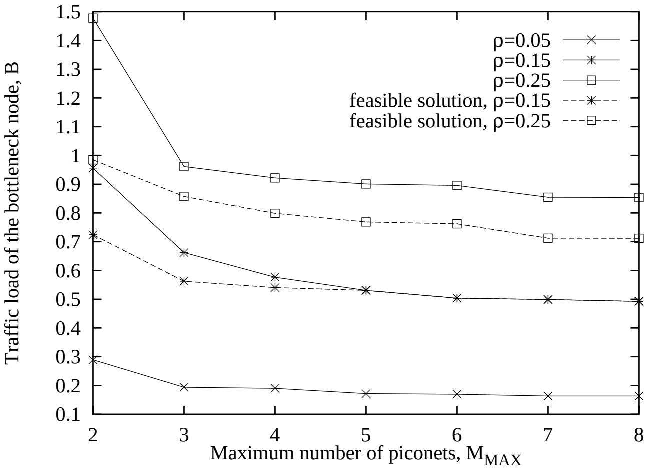

Figure 2. Traffic load of the most congested node in the network versus the maximum number of piconets and for $\rho = 0.05, 0.15,$ and 0.25. Results are obtained for $N = 12$, $C = 6$, and by forcing 3 nodes to be slaves and 2 nodes to be masters. The curves labeled by *feasible solution* are related only to topologies that meet the capacity constraints.

traffic flowing over each source-destination connection as well as in the source-destination connections that were created. The results suggested that a topology attained by solving the min-max optimization problem is surprisingly robust to changes in the traffic demand.

Here, we focus on the performance of the BT-WPAN topology as the maximum number of piconets, M_{MAX}, varies. The results presented in this section are derived for $Q = 10$ and a piconet radius equal to $Q\sqrt{2}/3$. We assume a network with 12 nodes and 6 traffic connections; 3 out of the 12 nodes are forced to be slaves. For the sake of simplicity, we assume that all the traffic links in the network are alike, and that $\rho_s = \rho$ for any traffic source, with ρ a varying parameter of the system. The extension to the case where SCO and ACL links are mixed, and different kinds of packets are used, is straightforward.

Plots are obtained by averaging the results of several runs, each of them corresponding to a different instance of the random variables of the system model. Each problem instance is solved by using the software tool CPLEX, which solves mixed integer problems by applying a branch and bound algorithm [15].

Figure 1 presents curves of the traffic load of the bottleneck node, B, as a function of the maximum number of piconets in the network and for different values of ρ. Notice that at least two piconets have to be formed, since each piconet cannot include more than 8 nodes. For $\rho = 0.25$, two curves are plotted in correspondence to the same value of the average source rate. In fact, in this case, not all the attained solutions to problem $\mathbf{P}$ fulfill the capacity constraints. In the plot, the curve labeled by *feasible solution* represents the performance of the feasible topologies only, while the curve labeled by just the value of ρ represents the network performance when the capacity constraints are neglected. Notice that in the latter case we may have $B > 1$. Figure 1 shows that the bottleneck traffic load decreases as M_{MAX} increases. This is because the greater the number of formed piconets, the smaller the number of slaves per piconet and, thus, the lower the traffic load of the masters. As expected, smaller ρ's correspond to lower values of B.

Figure 2 shows similar results for a network scenario where 2 out of the 12 nodes are forced to be masters. In this case, infeasible solutions are attained also for $\rho = 0.15$, and, for all ρ's, the values of B are higher than in the case where there is no fixed master. This suggests that fixing the role of some nodes in the network leads to a more uneven traffic distribution, thus reducing the network capacity.

Figure 3 presents the number of feasible solutions, i.e., solutions to problem $\mathbf{P}$ meeting the capacity constraints, normalized to the total number of problem instances that we solved. Two out of the total number of nodes in the network are forced to be masters. Results are plotted versus

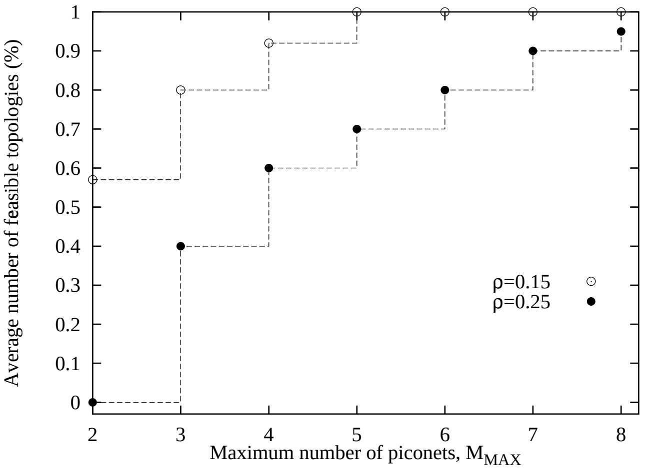

Figure 3. Average number of attained topologies satisfying the capacity constraints, normalized to the total number of topologies obtained by solving different instances of the optimization problem. Results are plotted versus the maximum number of piconets and for $\rho = 0.15, 0.25$. We assume $N = 12$, $C = 6$, and that 3 nodes are forced to be slaves and 2 nodes to be masters.

the maximum number of piconets and for $\rho = 0.15$ and 0.25. For $\rho = 0.15$ and $M_{MAX} \geq 5$, all the attained solutions satisfy the capacity constraints. This is in agreement with the results shown in Fig. 2, where the curves corresponding to $\rho = 0.15$ overlap for $M_{MAX} \geq 5$. On the contrary, for $\rho = 0.25$, we get some infeasible topologies even for $M_{MAX} = 8$. This is because increasing M_{MAX} reduces the masters traffic load but, on the other hand, makes the inter-piconet traffic grow, thus increasing the load of the bridge nodes.

Finally, Figure 4 shows the average value of the actual number of piconets that are created in the BT-WPAN when two nodes are forced to be masters and M_{MAX} and ρ vary. Only the feasible topologies are considered. We observe that the average number of piconets decreases as ρ grows, and tends to saturate as we consider larger values of M_{MAX}'s. These results confirm that the benefit of increasing the maximum number of piconets fades away as M_{MAX} grows, due to the increase in the inter-piconet traffic.

To conclude, we can fix M_{MAX} on the basis of the maximum level of system complexity and of inter-piconet interference that we consider to be acceptable. Once M_{MAX} is fixed, the proposed centralized procedure gives the optimal BT-WPAN topology supporting the required traffic connections, provided that such a topology exists.

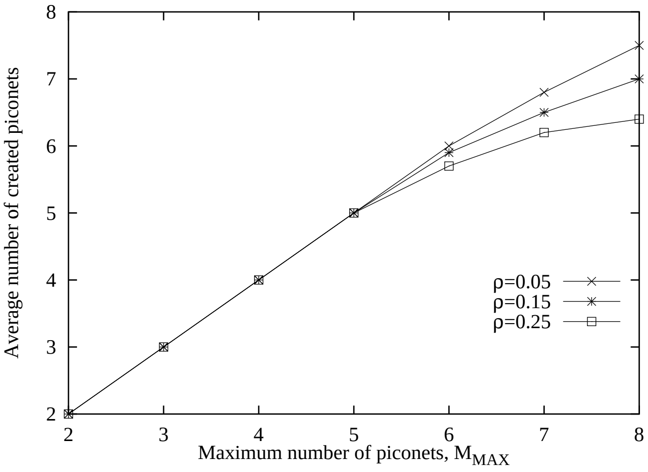

Figure 4. Average number of piconets that are actually created in the network topology as a function of the maximum number of piconets and for different values of ρ. Results are obtained for $N = 12$, $C = 6$, and by forcing 3 nodes to be slaves and 2 nodes to be masters.

4 A Distributed Approach

The optimization problem described in the previous section requires as input detailed system information, and is not suited for a distributed implementation, both for the algorithm characteristics, and for its intrinsic complexity, which forced us to deal with a limited number of network nodes. Because of these limitations of the min-max formulation, it is necessary to devise simple distributed heuristics which can be easily implemented and can be applied even to large BT-WPANs.

In the following, we consider a BT-WPAN with given topology, and discuss two distributed procedures to handle topology changes. The first procedure allows the insertion of a new node in the WPAN; the second deals with the removal of a network node. Both procedures aim at satisfying the Bluetooth technology constraints, while providing full network connectivity, high throughput, and reduced overhead due to control messages. We observe that the procedure for the insertion of a new node into the network also allows the insertion of more than one nodes at a time. Thus, it can be used either to construct a BT-WPAN incrementally, i.e., one node at a time, or to form the network topology from scratch, given an initial set of Bluetooth devices.

4.1 The Node Insertion Procedure

A node wishing to join the BT-WPAN starts an inquiry procedure by broadcasting *ID (Identity)* packets [1]. The nodes in its proximity, which are listening on the predefined channel for inquiry messages, respond with a *FHS (Frequency Hop Synchronization)* packet if they are willing to accept a new neighbor. When more than one nodes reply, the new node has to decide which node it should connect to. The decision can be made based on the responses that the new node receives and on the information it can acquire on the nodes in its proximity.

We consider that a Bluetooth device can be classified based on its physical characteristics, its current role in the WPAN, and the amount of traffic it transmits and receives, i.e., the total traffic that it generates, relays, or receives as a destination. We denote the generic node class with the triplet (x, y, z), where:

$$x = \begin{cases} p_1: & \text{general characteristics} \\ p_2: & \text{high computational capabilities and large battery capacity} \\ p_3: & \text{high computational capabilities and not specified battery capacity} \\ p_4: & \text{large battery capacity and not specified computational capabilities} \end{cases}$$

$$y = \begin{cases} r_1: & \text{role not specified} \\ r_2: & \text{slave} \\ r_3: & \text{master} \\ r_4: & \text{slave \& bridge} \\ r_5: & \text{master \& bridge} \\ r_6: & \text{master already connected to 7 active slaves} \end{cases}$$

$$z = \begin{cases} l_1: & \text{load not specified} \\ l_2: & \text{low traffic load} \\ l_3: & \text{high traffic load} \\ l_4: & \text{null, i.e., new node with no established connection.} \end{cases}$$

(The node traffic load is defined as low if it is below a certain threshold, as high otherwise.)

According to the Bluetooth specifications, a node performing an inquiry can either use a General Inquire Access Code (GIAC) or a Dedicated Inquiry Access Code (DIAC). By employing the GIAC, the node addresses any device in its proximity, while through a DIAC it can inquire for a particular type of devices. Since only 63 codes can be used for dedicated inquiry, we make class (p_1, r_1, l_1) correspond to the GIAC, and consider only the most meaningful classes out of all others. In particular, it seems reasonable to assume that a node does not inquire for devices with a high traffic load; thus, we define the classes identified by the DIACs as follows:

47 classes: (x, y, z) with $x = p_1, p_2, p_3, p_4$; $y \in \{r_1, r_2, r_3, r_4, r_5, r_6\}$; $z \in \{l_1, l_2\}$; and $(x, y, z) \neq (p_1, r_1, l_1)$;

4 classes: $(x, \cdot, l_4)$ with $x = p_1, p_2, p_3, p_4$.

Observe that a node wishing a *fast* connection to the WPAN will likely send out a general inquiry to solicit a response from any available node in its proximity. Instead, a node aiming at a *good* connection in the network, i.e., at joining a piconet with low traffic load or playing a particular role, will use a dedicated inquiry.

Next, we look at the inquiry response which is carried by the FHS packet. We notice that an FHS packet includes the indication of the device class, plus 5 bits that can be employed to convey further information. The 5 bits are the 2 bits reserved for future use and the 3 bits of the AM_ADDR field that are not used in an inquiry response. We assume that the 5 bits convey the following information:

2 bits: the battery charge level (e.g., below 25%, between 25% and 50%, between 50% and 75%, higher than 75%);

2 bits: the level of the node traffic load;

1 bit: whether the node belongs to an *isolated* piconet. We define a piconet as *isolated* if it is not connected with any other piconet or all the neighboring piconets are connected with this piconet only. The bit is set to 1 for a node belonging to an isolated piconet, and to 0 otherwise.

Let α be the node starting the inquiry procedure. As mentioned above, depending on the responses received from the neighboring nodes, α has to decide which node it will page. A node replying to α may belong either to an isolated or a not-isolated piconet. In addition, it may be

1. a master with less than 7 connected active slaves;
2. a slave;
3. a slave & bridge;
4. a master & bridge;
5. a master with already 7 connected active slaves;
6. a new node which, like α, wishes to join the BT-WPAN.

α selects the node to page according to the following order of preference.

1. **Master (or master & bridge) belonging to an isolated piconet.**
   If α receives a response from more than one masters

(or master & bridge nodes) belonging to an isolated piconet, it selects the one with less than 7 active slaves and the lowest traffic load. If there are more than one nodes in such a situation, the level of battery charge is considered, followed by the distance of the node from α. Notice that α can estimate the distance from each of the responding nodes through the associated RSSI (Received Signal Strength Indicator). Denote the chosen master with μ. Node α pages μ and creates a new piconet, where α is the master and μ is a slave. Afterwards, the two nodes switch their roles so that α becomes a slave in the piconet controlled by μ.

Then, if α receives a response also from a node that does not belong to an isolated piconet, it acts as follows.
(i) If the responding node is a master, or a master & bridge, with less than 7 active slaves, α pages such a node and creates a new piconet. Through a master-slave switching, α becomes a slave in the piconet of the selected node and a bridge toward the master (or master & bridge) belonging to the isolated piconet.
(ii) If the responding node is a slave (slave & bridge), or a master (master & bridge) with already 7 active slaves, α creates a new piconet including such a node.

2. **Slave (or slave & bridge) belonging to an isolated piconet.**
   Two different situations may occur.
   (i) There are not other nodes connected to the scatternet, that reply to the inquiry made by α. In this case, we may have the following situations: *(a)* α has enough processing and energy capabilities to be a master. Then α forms a new piconet by paging one or more of the slaves that have responded to its inquiry. Such slave nodes become bridges between the new piconet and their former piconet. The slaves to be paged can be also selected by α on the basis of their traffic load, battery status and spatial distance. Assume that each piconet is identified by a short string of bits, namely less than 5 bits long, and that the piconet identifier is known to all the nodes in the piconet [7]. A slave paged by α could notify this information by using the 5 bits available in the FHS packet carrying its paging response. In this way, α has the possibility to interrupt the paging procedure whenever it contacts nodes belonging to piconets that have been already interconnected. *(b)* α wishes to act as a slave. α chooses the node to page among the available ones on the basis of the traffic load, the level of battery charge, and the spatial distance. Node α forms a new piconet with the selected device. Afterwards, the two nodes exchange roles so that in the new piconet α becomes a slave and the selected device becomes the master and a bridge toward its former piconet.
   (ii) α receives a response from other nodes, which do not belong to an isolated piconet. In this case, α tries to connect the node belonging to an isolated piconet with the rest of the scatternet. It selects one of the nodes connected to the scatternet according to the following order of preference: slave, slave & bridge, master, master& bridge, master with 7 active slaves. If necessary, a further selection is made on the basis of the following criteria: traffic load, level of battery charge, and spatial distance. Then, α creates a new piconet including both the selected node and the slave (slave & bridge) belonging to the isolated piconet.

3. **Master not belonging to an isolated piconet and with less than 7 connected active slaves.**
   Among the available master nodes, α selects the one with the lowest traffic load. If there are more than one nodes with the same traffic load, the level of battery charge is considered, followed by the distance of the node from α. Giving preference to closer nodes avoids a large overlapping between piconets and thus reduces the inter-piconet interference. Let us denote the chosen master with μ. Node α pages μ and creates a new piconet, where α is the master and μ is a slave. Afterwards, the two nodes switch their roles so that α becomes a slave in the piconet controlled by μ.

4. **Slave not belonging to an isolated piconet.**
   As in case 2.*i*, two possible cases are considered.
   (i) α has enough processing and energy capabilities to be a master. Then α forms a new piconet by paging one or more of the slaves that have responded to its inquiry. Such slave nodes become bridges between the new piconet and their former piconet.
   (ii) α wishes to act as a slave. α chooses the node to page among the available ones and forms a new piconet with the selected device. Afterwards, the two nodes exchange roles so that in the new piconet α becomes a slave and the selected device becomes the master and a bridge toward its former piconet.

5. **Slave & bridge not belonging to an isolated piconet.**
   As before, two possible cases are considered.
   (i) α has enough processing and energy capabilities to be a master. Node α selects the slave & bridge node to page on the basis on the following three criteria: *(a)* traffic load, *(b)* battery charge, and *(c)* spatial distance. A new piconet is created, where α acts as the master and the selected node as a slave.
   (ii) α wishes to act as a slave. A new piconet is formed, where α is a slave and the selected node is the master and a bridge toward its former piconet.

6. **Master & bridge not belonging to an isolated pi-**

conet.
Among the available master & bridge nodes, α selects the one to page on the basis of the following criteria: *(a)* traffic load, *(b)* battery charge, and *(c)* spatial distance. After α has created a new piconet, it switches role with the selected node so that α becomes a slave in the piconet controlled by the chosen master & bridge node.

7. **Master not belonging to an isolated piconet and with already 7 connected active slaves.**
   Among the available nodes, α selects the one with the lowest traffic load. If there are more than one nodes with the same traffic load, the level of battery charge is considered as choice criterion, followed by the distance of the node from α. A new piconet is created, whose master is α. Then, there are two possible ways to proceed. *(i)* In the new piconet, α remains a master, and the selected node acts as a slave & bridge. *(ii)* The two nodes exchange roles. To do so, the selected node puts one of its slaves in park mode and takes α as an additional slave. The slave in park mode can decide to search for a new piconet by performing an insertion procedure on its turn. Otherwise, α and any of the other nodes in the piconet have to be put alternately in park mode.

8. **New node.**
   Node α pages the new node, thus creating a new piconet where it plays the role of master. Then, the two nodes can switch their roles if they wish to do so. α can also include in its piconet other new nodes that responded to its inquiry. However, in order to maintain the BT-WPAN topology connected, either α or some of the new nodes connected to α have to page a node that is already part of the BT-WPAN.

4.2 The Node Removal Procedure

The changes in the topology caused by a node leaving the network depend on the role that the node played in the BT-WPAN. Below, the possible cases are discussed.

1. The node was a slave: The node is simply removed from the network without involving any other modification of the topology.

2. The node was a master: The slaves belonging to its piconet are seen as new nodes that need to be reconnected to the BT-WPAN, hence an insertion procedure is performed for each of them. The bridge nodes remain connected to the network through the other piconet(s) they belong to.

3. The node was a master & bridge: This case is handled in the same way as case 2.

4. The node was a slave & bridge: If other bridges can replace the node, it is simply removed from the network. Otherwise, an alternative bridge node has to be found. To this end, the master of the piconet will start an inquiry procedure. If it cannot find any bridge toward the targeted piconet, it will ask its slaves to perform the inquiry. If no node is in the transmission range of any node in the rest of the BT-WPAN, then the piconet will remain disconnected.

5 Conclusions and Future Work

In this paper, we overviewed and extended a min-max formalization of the BT-WPAN topology formation problem. The min-max problem solution provides topologies which minimize the traffic load of the most congested node in the network while meeting the constraints on the BT-WPAN structure and capacity. By varying the maximum number of piconets that can be created, we derived the performance of the attained solutions as the requirements on the throughput and on the role played by some of the network nodes change. The results can be used to find the optimal trade-off between system complexity and network efficiency. However, the high complexity of the min-max formulation forced us to solve the problem in a centralized manner and to keep the number of network nodes small. Then, to overcome such a limitation, we discussed the key building blocks for a distributed solution approach to the BT-WPAN topology formation problem. We outlined two procedures to handle the insertion and the removal of a node in/from the BT-WPAN, in a distributed fashion. Although these procedures may generate sub-optimal topologies, they can be easily implemented and are designed to deal with a large number of nodes.

Future research will focus on the performance evaluation of the proposed distributed algorithms, in terms of latency in reacting to topology changes, network throughput, and overhead due to control messages exchange. When a small number of nodes is considered, the results obtained through the centralized optimization problem will provide a useful term of comparison for the distributed algorithms. Finally, it will be necessary to develop procedures for periodical management and reconfiguration of the BT-WPAN topology, so that the network characteristics can progressively adapt to a changing networking scenario.

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