A General Methodology and Key Metrics for Scatternet Formation in Bluetooth

Francesca Cuomo, Tommaso Melodia
INFOCOM Department, University of Rome "La Sapienza", Via Eudossiana 18, 00184, Rome, ITALY

***Abstract* - To fully exploit the capabilities of Bluetooth for the deployment of wireless ad-hoc networks, the scatternet concept has been proposed. A scatternet is constituted by an overlapping of simple structures called piconets, each composed of up to eight devices sharing the same radio channel. A scatternet may present different topological configurations, depending on the number of composing piconets, the role of involved devices and the configuration of the links. This paper presents a general methodology for scatternet formation and proposes metrics that can be used to evaluate scatternet performance. Several numerical examples are presented and discussed, highlighting the impact of metric selection on scatternet performance.**

I. INTRODUCTION

Bluetooth (BT) is a promising short range, low power and low cost technology for the deployment of wireless ad hoc networks. It is packet oriented and supports about 1 Mbit/s in a so-called "piconet", where up to 8 BT devices can simultaneously inter-connect. The radius of a piconet is about 10 meters. No network infrastructure is envisaged: self-organization and peer communication will lead to a complete "ad-hoc connectivity". The multiple access technique is FHSS-TDD (Frequency Hopping Spread Spectrum – Time Division Duplexing) [1][2]. Two BT units exchange information by means of a master-slave relationship. Master and slave roles are dynamic: the device that starts the communication is the master, the other one is the slave.

One of the key issues associated with the BT technology is the possibility of dynamically setting-up and tearing down piconets while interconnecting them in a "scatternet", i.e., an overlapping of piconets as in Fig. 1. Devices number 1, 5 and 6 in Fig. 1. are masters; devices 4 and 7 are slaves in different piconets and on a time division basis; act as "bridge" and forward traffic to devices belonging to different piconets.

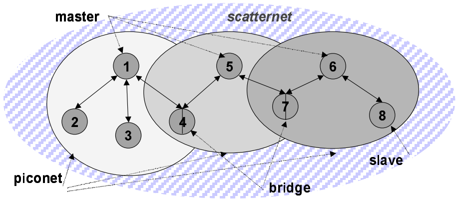

Fig. 1 - An example of scatternet made up of 3 piconets

Clearly, we can think of many alternatives to form a scatternet out of the same group of *N* devices. The way a scatternet is formed considerably affects its performance.

In this paper, we define a methodology for the analysis of the scatternet formation issue. Section II briefly summarizes the state of the art in scatternet formation. In Section III, we present the methodology. Section IV presents metrics that can be used to evaluate a scatternet; related numerical results are shown in Section V. Finally, Section VI reports the main conclusions.

II. RELATED WORKS

Scatternet formation has recently received a significant attention in literature. Existing works on this topic concentrate on two main aspects: i) formation of a scatternet by means of a distributed algorithm [3][4][5][6][7][8]; ii) formation of an optimal scatternet, by using centralized algorithms [9], where the optimality is defined according to suitable criteria.

In the first case, the aim is to form a connected BT scatternet without *optimizing* specific performance and by relying on distributed algorithms. A second class of works concentrate on the *optimization* of the scatternet topology. To the best of our knowledge this issue is faced for the first time in [9] where a *centralized* optimization aims at minimizing the load of the most congested node in the network.

Finally, works exist that, even if not strictly concerned with scatternet formation, can be of interest in our framework. Such papers try to optimize the use of the resources of an already formed scatternet, by focusing on scheduling mechanisms that operate between adjacent piconets [2].

In this paper, we focus on two main points:

- definition of a methodology for the scatternet formation, according to suitable metrics, based on a representation in a matrix form, which turns out to be a very simple and effective design tool; this methodology can be used to generate scatternets by means of both centralized and distributed approaches;
- identification of several metrics that can be used to form and evaluate scatternets; we emphasize the difference between traffic dependent and traffic independent metrics and we show some numerical results.

III. THE SCATTERNET FORMATION ISSUE

Before addressing the scatternet formation issue it is useful to define a methodology for its representation.

A. Scatternet representation

We assume that a master can not contemporarily be a slave in any other piconet, since this case leads to inefficient bandwidth usage ([10]); in fact, when the master communicates as slave, no communication can occur in the piconet where it plays the role of master. As a consequence a scatternet can be described as a *bipartite* graph, i.e., a graph whose nodes are divided in two disjoint sets. A link may exist between two nodes only if they belong to different sets.

A scatternet may thus be represented by a rectangular MxS binary matrix **B**, where M and S are the number of masters and slaves respectively. Element b_{ij} in the matrix equals 1 iff slave j belongs to master i's piconets ([10]).

For instance, the scatternet of Fig. 1 may be represented by the following matrix **B** (1a). Besides, the path between the pair of nodes (h, k) may be expressed by another MxS matrix $\mathbf{P}^{h,k}(\mathbf{B})$, whose element $p_{ij}^{h,k}$ equals 1 iff the link between master i and slave j is part of the path between node h and node k ($1 \le h, k, i, j \le N$)). As an example, and referring again to Fig. 1, the path between node 2 and node 8 can be represented by the matrix $\mathbf{P}^{2,8}(\mathbf{B})$ of Eq. (1b).

$$\mathbf{B}=\begin{array}{c} \\ 1 \\ 5 \\ 6 \end{array}\begin{array}{c} \begin{matrix} 2 & 3 & 4 & 7 & 8 \end{matrix} \\ \begin{pmatrix} 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 \end{pmatrix} \end{array} \text{(a)} \qquad \mathbf{P}^{2,8}(\mathbf{B})=\begin{array}{c} \\ 1 \\ 5 \\ 6 \end{array}\begin{array}{c} \begin{matrix} 2 & 3 & 4 & 7 & 8 \end{matrix} \\ \begin{pmatrix} 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 \end{pmatrix} \end{array} \text{(b)} \qquad (1)$$

Let us now investigate how to represent a scatternet in the above matrix form, starting from a given set of N nodes. To describe the considered set of nodes and the relevant possible relationships we use the *NxN adjacency matrix* $\mathbf{A}=[a_{ij}]$, whose element a_{ij} equals 1 iff device j is in the radio range of device i (i.e., j can directly receive the transmission of i).

Given a set of N nodes Z and an adjacency matrix **A**, we can build the MxS matrix $\mathbf{B}=[b_{ij}]$ by associating the rows to a Z_m non empty subset of M nodes in Z, and the columns to a Z_s non empty subset of S nodes in Z, with $N=M+S$, $Z_m \cap Z_s = \{0\}$ and $Z_m \cup Z_s = Z$. The resulting matrix **B** may be considered representing a "BT-compliant" scatternet with M masters and S slaves if the properties of Tab. 1 apply.

Property	Property formalization
1: *each master is connected at least to a slave*	$\sum_{j=1}^{S} b_{ij} \ge 1 \quad \forall i \in M$
2: *no more than seven slaves belong to a piconet*	$\sum_{j=1}^{S} b_{ij} \le 7 \quad \forall i \in M$
3: *each slave is connected at least to a master*	$\sum_{i=1}^{M} b_{ij} \ge 1 \quad \forall j \in S$
4: *the resulting network is connected*	the matrix B does not have a block structure, rows permutation notwithstanding

Tab. 1 – BT properties

B. A methodology for scatternet formation

By exploiting the above representation, we can introduce a general methodology that can be used: i) to form optimized scatternets on the basis of suitable metrics by means of both centralized and distributed approaches; ii) to evaluate the ensuing performance. In Fig. 2 we report a block scheme of this methodology.

The upper part of the figure is concerned with a centralized approach:

- block 1 randomly generates communication scenarios;
- block 2 identifies and lists all the "BT-compliant" scatternets that may be obtained starting from the scenarios produced by the first block;
- block 3 evaluates performance parameters of the scatternets identified by the second block by means of suitable metrics, which can be traffic-independent or traffic-dependent;
- block 4 chooses the optimal scatternet according to the chosen metric.

As for the first block, the generation of the scenario proceeds by complying with these constraints:

- every node must be able to connect to at least another node, the radio range, d_{max}, is assumed to be 10 meters;
- groups of isolated devices are not allowed (otherwise splitted scatternets could arise).

A new tentatively generated node can enter the scenario iff its distance from its closest node is less than or equal to d_{max}. The generated scenario is then represented by an NxN adjacency matrix **A**.

The function of the second block is to exhaustively identify and list all "BT-compliant" scatternets that may be obtained from the scenario represented in **A**. Let be:

- M the number of masters in the scatternet, with $M_{min}=\left\lceil \frac{N}{7+1} \right\rceil \le M \le M_{max}=\left\lfloor \frac{N}{2} \right\rfloor$; as regards M_{max} we assume to limit its value to $\left\lfloor \frac{N}{2} \right\rfloor$ since a number of masters greater than half the nodes introduces inefficiencies (e.g., interference) without bringing benefits to the scatternet;
- **A'** a rectangular Mx(N-M) adjacency matrix, which represents the complete set of possible connections between masters and slaves deriving from a particular way of selecting the M masters among the N nodes.

The number of possible different **A'** matrices is equal to $\sum_{M=M_{min}}^{M_{max}} \binom{N}{M}$, since there are $\binom{N}{M}$ possible ways of selecting M masters among the N nodes.

From each **A'** matrix, a number of **B'** matrices is derived, each representing a subset of the possible connections among nodes in **A'**. Those which respect properties 1-4 represent all and alone the scatternets obtainable with that choice of masters and constitute the output of the block (**B** matrices).

In the third block, every **B** matrix is evaluated according to a metric that corresponds to a particular optimization target function. Finally, the fourth block chooses the scatternet whose representing matrix **B** optimizes (maximizing or minimizing) the selected metric.

The output of the overall process is the scatternet with the optimal topology (according to the metric applied). This process requires complete knowledge of the scenario characteristics and can be realized only by means of centralized algorithms. This approach has two important advantages: i) allows identifying all possible "BT-compliant" scatternets deriving from a given scenario; ii) allows to easily apply different metrics to the scatternet formation process and to evaluate the resulting scatternet performance. Clearly these pros have to be paid with the complexity of examining all "BT-compliant" scatternets.

Conversely, the lower part of Fig. 2 is concerned with a distributed approach, analyzed into details in [11]. Starting from the same scenario of the centralized approach, a distributed algorithm is applied to form a scatternet, with the same metric of the previous case. The resulting scatternet may be compared, on the basis of the selected metric, to the one formed in a centralized way.

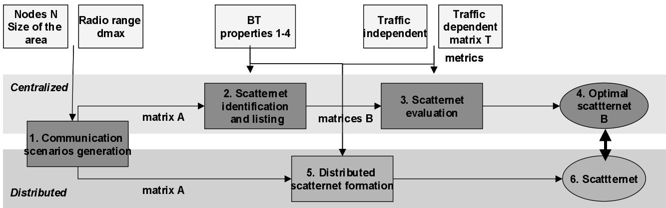

Fig. 2 – Scheme of the applied methodology

IV. METRICS FOR THE SCATTERNET EVALUATION

The methodology to form scatternets exploits suitable metrics that can be either dependent or independent on the traffic loading the scatternet. In the Traffic Independent (TI) case, the scatternet is formed without *a priori* knowledge of traffic relationships among involved devices. The scenario is described only by means of the adjacency matrix **A**.

If traffic relationships between nodes (e.g., flows at given data rates) have to be taken into account, they can be conveniently described by a traffic matrix, **T**. In the following, we refer to this case as Traffic Dependent (TD).

In this Section, we will introduce several metrics; we are aware that such metrics have pros and cons. However, we present them to examine and discuss their characteristics so that the network engineer can chose the most suitable one by comparing them via a performance evaluation study.

A. TI metrics: scatternet with maximum capacity

A first TI metric is the overall capacity of the scatternet, which has to be maximized. The capacity of each piconet depends on adopted intra-piconet and inter-piconet scheduling policies [2]. We assume that each master allocates the same portion of capacity to each connection with any of its slaves, and that the same amount of capacity is allocated to the two directions of each communication: master-to-slave and slave-to-master. Finally, we assume that each bridging node spends the same time in each of the piconets it belongs to. These assumptions are adopted for the sake of simplicity; the proposed methodology does not depend on them and can be applied for whatever scheduling policies.

The scatternet capacity will be evaluated by normalizing its value to the overall capacity of a piconet (i.e. ≈ 1 Mbit/s).

Let us define two MxS matrices, $\mathbf{O}_{TI}(\mathbf{B})=[o_{ij}]$, and $\mathbf{D}_{TI}(\mathbf{B})=[d_{ij}]$, with $o_{ij}=b_{ij}/m_j$ and $d_{ij}=b_{ij}/s_i$ (j=1,…,S and i=1,…,M). In these matrices s_i denotes the number of slaves connected to master i and m_j denotes the number of masters connected to slave j:

$$s_i = \sum_{j=1}^{S} b_{ij} \quad for\ i = 1,...,M \qquad m_j = \sum_{i=1}^{M} b_{ij} \quad for\ j = 1,...,S \qquad (2)$$

The matrix **O**(**B**) represents portions of capacity a slave may "spend" in the piconets it is connected to. The **D**(**B**) matrix represents portions of capacity the masters may "dedicate" to each of their slaves. The overall capacity of the scatternet is given by the sum of the capacities of all links. The capacity of link (*i, j)* is the minimum between the capacity o_{ij} and the capacity d_{ij}.

Let us define the *normalized capacity* $c_{TI}(\mathbf{B})$ and the relevant MxS matrix $\mathbf{C}_{TI}(\mathbf{B})$ as

$$c_{TI}(\mathbf{B}) = \sum_{i=1}^{M}\sum_{j=1}^{S}\min(o_{ij}, d_{ij}) \qquad \mathbf{C}_{TI}(\mathbf{B}) = [c_{ij}] = \lfloor \min(o_{ij}, d_{ij}) \rfloor \qquad (3)$$

The matrix $\mathbf{C}_{TI}(\mathbf{B})$ states the normalized capacity of each link of the scatternet. As an example, let us consider the scatternet of Fig. 1. The correspondent matrices $\mathbf{O}_{TI}$ (**B**), $\mathbf{D}_{TI}(\mathbf{B})$ and $\mathbf{C}_{TI}$ (**B**) are:

$$\mathbf{O}_{TI}(\mathbf{B}) = \begin{matrix} & 2 & 3 & 4 & 7 & 8 \\ 1 & 1 & 1 & 1/2 & 0 & 0 \\ 5 & 0 & 0 & 1/2 & 1/2 & 0 \\ 6 & 0 & 0 & 0 & 1/2 & 1 \end{matrix} \quad \mathbf{D}_{TI}(\mathbf{B}) = \begin{matrix} & 2 & 3 & 4 & 7 & 8 \\ 1 & 1/3 & 1/3 & 1/3 & 0 & 0 \\ 5 & 0 & 0 & 1/2 & 1/2 & 0 \\ 6 & 0 & 0 & 0 & 1/2 & 1/2 \end{matrix} \quad \mathbf{C}_{TI}(\mathbf{B}) = \begin{matrix} & 2 & 3 & 4 & 7 & 8 \\ 1 & 1/3 & 1/3 & 1/3 & 0 & 0 \\ 5 & 0 & 0 & 1/2 & 1/2 & 0 \\ 6 & 0 & 0 & 0 & 1/2 & 1/2 \end{matrix}$$

The resulting normalized capacity is $c_{TI}(\mathbf{B})$=3 (≈ 3 Mbit/s).

The evaluation above is approximate, mainly for two order of reasons:

1. interference from co-located piconets may lower the capacity of the scatternet;
2. switching overhead, caused by bridging slaves that change piconets, may lower the capacity of the scatternet.

The interference effect can be taken into account by applying a multiplicative factor to Eq. (3). This factor is derived from results presented [12] and applied in the evaluation of the numerical results presented in Section V.

We assume that a bridge slave switches from a piconet to another with a mean time period equal to an IP packet transmission time (about 20 BT time slots). This results in a quantifiable value of loss of capacity (≈2 slots per switch), which is considered in the numerical results presented in Section V.

B. TD metrics: scatternet with maximum residual capacity or minimum average load

We consider two TD metrics: i) the so-called *residual capacity* (i.e., the capacity that remains available in a scatternet, after that all pre-defined traffic relationships have been satisfied), which has to be maximized; ii) *nodes' average load*, to be minimized.

The evaluation of the above metrics is traffic dependent, and as such, is obviously tied to and reliant on the adopted routing strategy. As an example, given a traffic relationship, for instance a data flow between device h and device k (with $1 \le h, k \le N$), the capacity that such flow requires from the overall scatternet depends on the number of hops that make up the path between device h and device k. In our analysis, we assume that a shortest path routing algorithm is applied.

To evaluate the metrics, we start by describing the traffic relationships with a NxN traffic matrix $\mathbf{T}=[t_{hk}]$, whose element t_{hk} represents the capacity, normalized with respect to the 1 Mbit/s capacity of a piconet, required by the (h, k) relationship ($1 \le h, k \le N$). We also denote by R the number of traffic relationships expressed by this matrix.

It is easy to see that the capacity required on each link by the traffic relationship between node h and node k is given by $t_{hk}\mathbf{P}^{h,k}(\mathbf{B})$.

The matrix representing the overall normalized capacity required on each link of a scatternet **B**, in the TD case**,** is given by:

$$\mathbf{C}_{TD}(\mathbf{B}) = \sum_{h=1}^{N}\sum_{k=1,k\neq h}^{N} t_{hk}\cdot \mathbf{P}^{h,k}(\mathbf{B}) = \left[e_{ij} = \sum_{h=1}^{N}\sum_{k=1,k\neq h}^{N} t_{hk}\cdot p_{ij}^{h,k} \right] \qquad (4)$$

The traffic relationships defined by the matrix **T** can be effectively supported by the scatternet **B** if the following conditions, that assure steady state, are verified**:**

$$\sum_{j=1}^{S} e_{ij} \le 1 \quad \forall i \in M \text{, and } \sum_{i=1}^{M} e_{ij} \le 1 \quad \forall j \in S \qquad (5)$$

Based on the above definitions, we can finally measure the capacity that remains available in a scatternet, after all traffic relationships expressed in the matrix **T** are satisfied. Recalling that the capacity of each link is assigned according to Eq. (3), the r*esidual capacity* metric, $r_{TD}(\mathbf{B})$, is given by:

$$r_{TD}(\mathbf{B}) = \sum_{i=1}^{M}\sum_{j=1}^{S}\left(c_{ij} - e_{ij}\right) \qquad (6)$$

According to this metric, a scatternet is optimal, when the value of $r_{TD}(\mathbf{B})$ is maximized.

Alternatively, we can adopt as metric the *nodes' average load*. To evaluate such a measure, we first calculate the total capacity required by the traffic relationships of matrix **T** as:

$$f_{TD}(\mathbf{B}) = \sum_{i=1}^{M}\sum_{j=1}^{S} e_{hk} \qquad (7)$$

Since a capacity required on a link gives rise to an equivalent load on two nodes, we can calculate the average load on each node, which we denote as $l_{TD}(\mathbf{B})$, as:

$$l_{TD}(\mathbf{B}) = 2\cdot f_{TD}(\mathbf{B})/N \qquad (8)$$

The minimization of the average load goes in the direction of a minimization of the average energy consumption.

C. Metrics associated to the path length

We define two other metrics that do take into account the path length. Let us denote the length of the path between device *h* and device *k* in a scatternet represented by a matrix **B** (expressed in number of hops) as:

$$h^{h,k}(\mathbf{B}) = \sum_{i=1}^{M}\sum_{j=1}^{S} p_{ij}^{h,k} \qquad (9)$$

The first metric that we introduce is the *average path length,* that shall be minimized*.* This metric corresponds to the path length averaged over all possible relationships among the *N* nodes in the TI case and over all *R* traffic relationships in the TD case:

$$\tilde{h}_{TI}(\mathbf{B}) = \sum_{h=1}^{N}\sum_{k=1,k\neq h}^{N} \frac{h^{h,k}(\mathbf{B})}{N\cdot(N-1)} \text{ or } \tilde{h}_{TD}(\mathbf{B}) = \sum_{(h,k)\in T,k\neq h} \frac{h^{h,k}(\mathbf{B})}{R} \qquad (10)$$

By minimizing these metrics we go in the direction of minimizing the end-to-end transfer delay.

The second metric is the *average path capacity,* defined as the capacity available in each path averaged over all possible relationships among the *N* nodes (a TI metric which has to be maximized). The metric is defined as:

$$a_{TI}(\mathbf{B}) = \frac{c_{TI}(\mathbf{B})}{\tilde{h}_{TI}(\mathbf{B})\cdot N\cdot(N-1)} \qquad (11)$$

V. NUMERICAL RESULTS

Numerical results presented in this section are obtained by applying the centralized methodology described in Section III.B (upper part of Fig. 2). Each of the following figures represents the area containing the scatternet; the x and y axes are measured in meters. The figures report nodes, their roles (master, slave or bridge) and radio links interconnecting them. Piconets are not shown to improve neatness.

A. Traffic independent metrics

This sub-section shows examples of scatternets resulting from the TI optimization. The scenario is constituted by 12 devices distributed in an area of 100x100 meters. The scatternet of Fig. 3a is obtained by selecting the one with maximum *normalized capacity*. It can be immediately noticed that it presents a structure made up by a line interconnecting all nodes; i.e., every node is connected with two other nodes only. The value assumed by $c_{TI}(\mathbf{B})$, evaluated as in Eq. (3), is 5.5; by taking into account also the switching overhead, $c_{TI}(\mathbf{B})$ decreases to 5.2727 and by considering also the interference effect it becomes 4.7151.

Although this scatternet is the one with maximum $c_{TI}(\mathbf{B})$, it presents large values of the average paths length, which could lead to high transfer delays; moreover, this characteristic, together with the peculiar scatternet structure, limits the effective capability of supporting traffic. In fact, long paths require more scatternet capacity to support the same traffic relationship. As an example, a single 500 kbit/s bi-directional flow between node 10 and node 12 in Fig. 3a would use all the scatternet capacity: the nodes along the path would spend half their time receiving traffic from one of the two directions and the remaining relaying the traffic in the opposite direction.

The peculiar structure produced by this metric is due to the following reasons:

1. the metric tends to favor scatternets formed by a large number of piconets, since each new piconet added to the scatternet increases the overall capacity;
2. the interference effect is not significant since the number of co-located piconets is low;
3. when the switching overhead effect is taken into account, a bridge loses capacity as a function of the number of piconets it is connected to; thus, high performance, in terms of capacity, are attained when a bridge node is connected to only two piconets.

These considerations explain why path lengths have to be taken into account when forming a scatternet. However, minimizing the path lengths without considering the capacity, could lead to undesirable scatternets too since if the nodes are distributed in a small area, the resulting scatternet presents a fully meshed topology where every slave is connected to every master. In this case the resulting capacity is low as a consequence of the high number of bridges connected to a high number of piconets.

Let us now look at Fig. 3b, which shows a scatternet maximizing the *average path capacity*. This metric seems to be the most suited to maximize network performance, since both capacity and path length are taken into account. The scatternet of Fig. 3b presents a capacity, $c_{TI}(\mathbf{B})$ equal to 4.667 (4.5271 including the switching overhead and 4.0483 taking into account also the interference effect). The overall capacity is smaller than the value obtained by maximizing the *normalized capacity*, but, while in that case the average path length was 4.33, and the resulting capacity available for a generic path was 0.0082, in the case of Fig. 3b the average path length is 2.81; the resulting capacity per path is 0.0109.

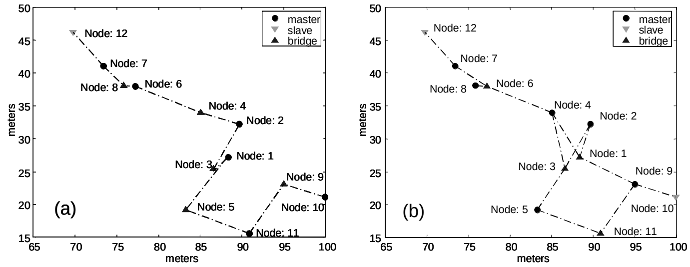

Fig. 3 – TI scatternet with maximum normalized capacity (a) and with maximum average path capacity (b)

B. Traffic dependent metrics

In this Section, we show results derived by applying the TD metrics. The scenario is composed of 10 nodes; the relevant traffic relationships are shown in Tab. 2. Fig. 4 depicts the scatternet with maximum $r_{TD}(\mathbf{B})$. It can be noticed that this metric suffers from the same drawbacks of the metric it is derived from (i.e., the *normalized capacity* one): it presents a linear structure.

In Fig. 5a we show the scatternet presenting the minimum *average path length* in the TD case. In this case the scatternet presents a more connected structure, with respect to that of Fig. 4. Finally in Fig. 5b we minimize the *average load*. The resulting nodes' loads are reported in the figure too, next to each node. Nodes' average load is 0.3058. In this case, it can be noticed that nodes that are located in specific positions (i.e., in a sort of barycentric position) have to take care of all the forwarding load, where by forwarding load we mean the traffic handled on behalf of other nodes. Nevertheless, since reducing the load means reducing the energy consumption, this scatternet consumes 70% of the energy required by the scatternet of Fig. 4 (whose average load is 0.4267).

Required normalized capacity	Traffic relationships
0.05	7↔8, 10↔8
0.08	1↔2
0.1	1↔5, 3↔4, 3↔9, 4↔9, 10↔7
0.125	5↔6, 6↔2

Tab. 2 – Traffic relationships

VI. CONCLUSIONS

In this paper we discussed the scatternet formation issue in BT by setting a framework for scatternet analysis based on representation in a matrix form, which gives rise to a very simple and effective design tool. We showed that it becomes quite easy to develop and apply new metrics with the proposed representation. We identified several metrics both in a traffic independent and in a traffic dependent context, and we showed the relevant numerical results. The analysis of numerical results permitted us to highlight the most suitable metric for a high performance scatternet formation.

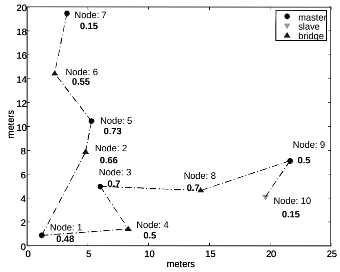

Fig. 4 – TD scatternet with maximum residual capacity

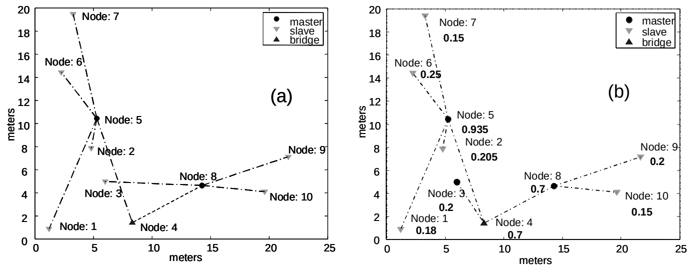

Fig. 5 – TD scatternet with minimum average path length (a) and with minimum average load (b)

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