Building Scatternets in High Rate Multi-hop Dynamic Personal Area Networks

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Abstract

The IEEE 802.15.3 standard allows the formation of scatternets in order to extend the network coverage. As numerous papers related to Bluetooth scatternet formation protocols pointed out, the performance of a WPAN highly depends on the scatternet structure. However, for IEEE 802.15.3 networks the issue of scatternet formation remains unsolved. In this paper we study the performance implications of different scatternet topologies. Starting our investigations with small scatternets we identify some drawbacks of the superframe management that lead to network resource wastage. Based on our findings, we propose a method to avoid the drawbacks of the current solution. Second, the performance of larger scatternets is investigated using different scatternet formation algorithms and different performance metrics. Our results reveal important relationships between the performance aspects and the construction of scatternets, which can serve as general guidelines for scatternet building algorithm design. (for ex.: packet lifetime vs. superframe size, etc.)

1 Introduction

Wireless Personal Area Networks (WPANs) are specialized ad hoc networks, which are envisioned to be used in offices, home applications, conference rooms, and vehicles. Typical WPAN applications are video conference, home theatre, and several cable replacement services. For such applications the communication is based on short-range connectivity; consequently, self-organization and interconnecting larger networks can introduce some important questions. The most popular WPAN standard is based on the IEEE 802.15.1 – Bluetooth standard. However, Bluetooth fails to offer enough bandwidth to support real-time multimedia applications. In this paper, we focus on the IEEE802.15.3 standard for High Rate WPANs [1] because it offers attractive features like high data transfer rate, Quality of Service provisioning and uses the worldwide available 2.4 GHz ISM unlicensed frequency band.

In order to build large WPANs, spanning over multiple radio hops, the IEEE 802.15 standards introduce the concept of scatternet formation. The performance of a WPAN highly depends on the scatternet structure; therefore, it is important to investigate issues related to scatternet topology formation. For Bluetooth networks, there are numerous results related to scatternet formation algorithms; however, in the 802.15.3 networks this issue still remains unsolved. In [2] an algorithm for ad hoc piconet initialization is proposed, which aims to increase the connection success between piconet members. However, the formation of scatternets and performance analysis is not presented in the paper. An extension of the 802.15.3 protocol is proposed in [3], where the authors describe and evaluate a protocol, which allows communication between piconet peers without the intervention of a central entity. This protocol could also be used in scatternets, but this issue was not investigated. An interesting idea for co-existing piconets is described in [4], where a beacon alignment mechanism is designed. The mechanism allows multiple piconets to use the same channel and the same superframe length by forcing a shifted superposition of the superframes. However, this mechanism requires careful piconet management and topology planning in order to avoid transmission errors caused by interfering nodes from different piconets.

This paper addresses some problems and corresponding solutions related to scatternet formation in 802.15.3 networks in order to increase the network throughput. To have a deeper understanding we have made several simulations in ns-2 [8] to investigate these networks. Different types of scatternet formation algorithms were investigated, the relation between the scatternet network parameters and network performance metrics were studied. These simulations were run on small-sized and also on large scale scatternet networks. In the first case the microscopic properties (details related to the piconets) of a scatternet are analyzed. The second group of analysis aims to examine the macroscopic behavior of the scatternets. For the large networks typical WPAN scenarios were considered, where a bunch of users are forming a multi-hop ad hoc network. For example we can imagine a conference room with many people, equipped with video and audio capable devices, which would like to communicate with each other. Based on our simulation results on small and large scatternets, we have found several interesting phenomena, which in the design phase of a scatternet formation algorithm can help us to increase the overall system performance.

The structure of the paper is organized as follows. Section 2 gives a short overview of the functional elements of the analyzed system. In Section 3 the methodology for our investigation and the scatternet generation algorithms are described. The analysis of the scatternet's performance is presented in Section 4. Finally Section 5 presents the conclusions and plans for future work.

2 Functional elements of the system

Like Bluetooth, the IEEE 802.15.3 employs a piconet-based topology, which is based on the master/slave paradigm; e.g. an elected device (the piconet coordinator - PNC) is responsible for coordination and piconet management. The MAC layer of the protocol employs a time-slotted superframe structure, constituted from the beacon, the optional channel request part (called Contention Access Period - CAP), and the data transmission part (called Contention Free Period - CFP). The beacon is used to carry information about channel time allocations (CTA) to the entire piconet; it is built and broadcasted by the PNC. The CAP is used by the nodes for association request/response, channel time request/response, and to exchange asynchronous data. The CFP can be composed of two kinds of CTAs, Guaranteed Time Slots (GTS) and Management Time Slots (MTS) in a TDMA frame structure. The MTS slots are used to carry management information from the slaves to PNC. The GTS slots are used by slaves for isochronous and asynchronous data communication. These slots can be dynamic or pseudo-static, depending on whether their relative position within the superframe can vary from one superframe to the next, or not. In the pseudo-static GTS slots special piconets (child and neighbor) can be created. The child and neighbor piconets use these time slots as the space to create and manage their own superframes.

The child piconet functionality is useful for extending the coverage area of a piconet. It is possible for the parent piconet to have more than one child piconet. In addition, it is also possible for a child PNC to allow a child piconet as a part of its own piconet. The child PNC is a member of the parent piconet and thus is able to exchange data with any DEV in the parent piconet. The child PNC is also a member of the child piconet and thus it is able to exchange data with any DEV in the child piconet. Thus, the child PNC will act as a gateway between the parent and the child piconet members. The network topology formed in this way is called scatternet.

The PNC is responsible to manage the allocation of piconet resources. It decides which node accesses the medium and when. In the context of 802.15.3 networks, the analyzed scheduling protocols are based on the Earliest Deadline First (EDF) and on the Shortest Remaining Processing Time (SRPT) algorithms [5][6]. In [6] the authors present a performance analysis, and show that SRPT outperforms EDF in terms of higher throughput and lower job response time. Therefore, we choose SRPT as the scheduler algorithm implemented in the PNCs. SRPT selects for service the pending job in the system with the least remaining service time. To do so, the length of the jobs has to be known by the scheduler. The policy is preemptive, so that if a new job arrives with a smaller service time than that remaining for the job currently in service, the scheduler switches immediately to service the newly arriving job. The SRPT policy is provably optimal: it guarantees the lowest mean response time for the overall system.

3 Methodology

Our primary goal was to relate the network performance metrics to the parameters of the scatternet. In order to have a proper modeling of the 802.15.3 networks we used a network simulator (ns-2), which is able to simulate the MAC protocol at packet level. However, besides the microscopic level (details related to piconets) we were also interested in the investigation of bigger scatternets. Therefore, for network topology generation we have developed a scatternet generator. In the generator the placement of nodes, the relations between piconets (parent-child roles) and the network traffic can be arbitrarily modified. To define the relations between piconets we have developed several scatternet formation algorithms. We also used Integer Linear Programming (ILP) techniques to generate scatternets with different optimization criteria. The interactions between the different modules of the simulator environment are presented in Figure 1.

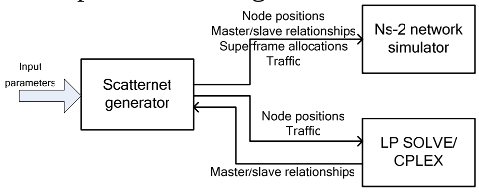

Figure 1: Relationship between the different simulator modules

In the scatternet generator, firstly a set of nodes are generated, which are uniformly distributed in a square area; the nodes were considered stationary during simulation. After generating the nodes the visibility graph was determined. Two nodes are connected in the visibility graph if their distance is less then the used radio range. In the next step, we apply one of the possible ways for scatternet formation: (i) we generate an optimal scatternet by using the LP-Solve/CPLEX toolkit or (ii) we build the scatternet with one of our algorithms implemented in the generator. Once the scatternet network is complete a random traffic matrix is generated, that will represent the load in the network.

The *random algorithm* selects the first master randomly then connects the maximum number of slaves possible to this master. The rest of masters are connected based on the parent-child relations. The *max-node algorithm* is similar to the previous algorithm, with the only difference that in this case the first master is elected based on the highest number of links in the visibility graph. In the *limited-node algorithm* the number of slaves connected to a master is limited to a certain value.

By using different scatternet formation algorithms, different types of scatternet topologies are obtained. The *random algorithm* represents a practical example, which could be easily realized in real life scenario. The *max-node algorithm* aims to minimize the number of piconets; consequently, it can be used to investigate how this number effects the scatternet performance. Such an algorithm could be built only on a top of an already existing topology, where the node can exchange information about their number of neighbors. The *limited-node algorithm* aims to form piconets with limited members; this approach could approximate a case when the PAN members want to form their own piconet without entering a bigger common piconet.

4 Scatternet formation analysis

To have a deeper understanding of the performance aspects of scatternets, firstly we investigated only small topologies with the ns-2 [8] network simulator with the 802.15.3 module presented in [9]. Based on the simulations we found several problems related to different aspects of inter-piconet traffic management. The results of these investigations and some solutions to the problems are presented in the first part of this section. After the experiments with small scatternets our interest was refocused towards the simulation of larger scatternets. We have generated scatternets with the algorithms presented in the previous section and used the ns-2 to run simulations on the obtained topologies.

The 802.15.3 MAC module was modified to support multi-hop scatternet simulations. Each simulation was run 10 times, for a duration of 200 seconds. To provide a realistic nature to our investigation we used video flows as traffic patterns generated by the MPEG4 traffic generator that used the Transform Expand Sample (TES) method presented in [7]. We assumed the wireless channel to be ideal; therefore, no noise, distortion, and other interference are present. In the simulations we will show that the superframe length strongly affects the system performance. In fact this value is in strong relation with the packet lifetime assumed to be 33ms in small scatternets and 133ms in large scatternets.

Performance metrics

The first and most obvious aspect in network characterization is the efficiency of channel utilization. Thus, during the performance analysis of the proposed techniques we considered this parameter as being the most important one. The main goal of all simulation runs was to analyze the service quality provided in the case of an increase in network load. In order to analyze the overall system performance, we used the following performance metrics:

- *Job Failure Ratio (JFR)* is a drop ratio metric; all the bursts dropped because of an expired deadline are characterized by this metric. For effective channel utilization the JFR should be as low as possible.
- *Response Time (RT)* is the time between passing a packet from the upper layer to the MAC layer, sending it, and receiving back a MAC layer acknowledgement. This metric is measured only for the successfully transferred bursts. Therefore, there can be cases when the system presents a good RT value, while JFR is very high.
- *Number of generated piconets:* while the large scatternet formation algorithms performance is analyzed, one of the most important metric is the number of piconets from which the scatternet is constructed.

4.1 Investigation on small topologies

During our investigation we observed that the parent-child superframe allocation mechanism has some drawbacks. In the following let us suppose a traffic which goes through two piconets with three nodes (nodes A-B from the child piconet and nodes B-C from the parent piconet). In Figure 2 two consecutive superframes of this scenario are presented, with their beacons and allocated traffic portions. Let us assume that between nodes A and B time-slots are allocated for their rt-VBR traffic (10 packets) in the N^{th} child superframe. This is announced in the child SF's beacon. In ideal case, to avoid unnecessary delays, the data transfer should immediately continue between B and C in the same (N^{th}) parent superframe. However, by the time when A sends the packets in the allocated interval, the beacon for the N^{th} parent superframe is already generated and broadcasted by the parent PNC. This means that even if there are free time-slots in the parent superframe, it cannot be used by B and C, since at the beacon generation time the parent PNC does not had information about the arriving packets to node B. Thus, the first ten packets can be transmitted between B and C only in the $(N+1)^{th}$ superframe. We can conclude, that packets generated/arrived during the interval of the N^{th} child superframe cannot be scheduled in the N^{th} parent superframe. This can lead to suboptimal scheduling, which means that a portion of the N^{th} parent superframe remains unutilized. This problem we call *predestination*, since the communication peers in the parent piconet are determined in advance, prior the events which happens in the following child piconet.

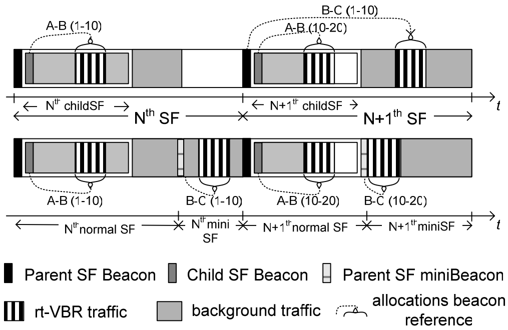

Figure 2: Multihop hierarchical superframe formation

To overcome the underutilization caused by *predestination*, we applied the concept of hierarchical superframes [10] for scatternets networks. Two kinds of superframes are used: the *normal superframe* with its *normal beacon*, and the *mini superframe* with its *mini beacon*, both having an arbitrary, dynamically changing size. In each superframe-period we have one normal superframe and one or more mini superframes. If the normal superframe does not extend the chosen superframe-period then we can introduce the mini superframes.

In the second part of Figure 2 we can see that by using the concept of hierarchical superframes is possible to schedule the packets (1-10) between B and C during the N^{th} parent superframe. This can be attributed to the possibility that mini superframes can be introduced in the normal superframes when there are free time-slots. In these mini superframes the parent PNC will be able to schedule the packets arrived to node B. Thus, the unused portion of the N^{th} parent superframe will be used for the data transfer between B and C.

For the simulation of small scatternets and the investigation of the *predestination* phenomena we created the following topology, depicted in Figure 3.

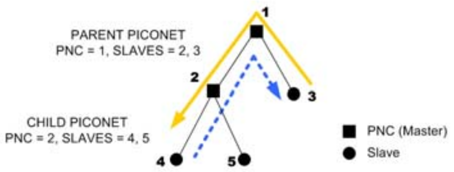

Figure 3: Investigated small topology

The topology consists of two piconets, where the parent piconet contains nodes 1, 2 and 3, and the child piconet contains nodes 2, 4 and 5. Each of the two traffic flows traverse three hops, from source node 3 to destination node 4 (downstream flow) and from source 4 to destination 3 (upstream flow), respectively. We compared the performance of the normal superframes (FIX) with the performance of the hierarchical superframes (HIER). Results related to the JFR and RT metrics are presented in the following figures. In all cases we applied an increasing number of traffic flows, while the overall network load remained constant (8 Mbps).

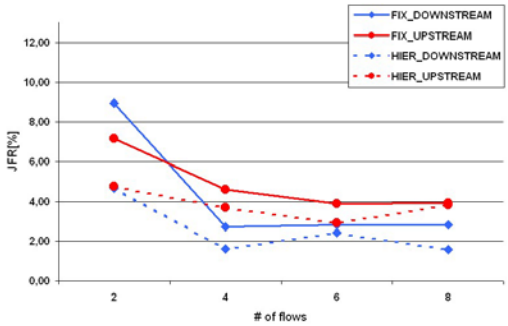

Figure 4: Job Failure Ratio (JFR)
SFSize = 4ms; CSFSize = 1.7ms

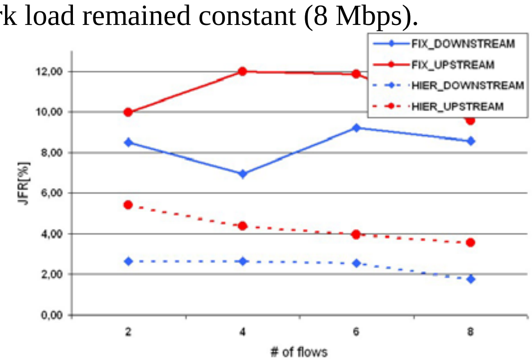

Figure 5: Job Failure Ratio (JFR)
SFSize = 6ms; CSFSize = 1.7ms

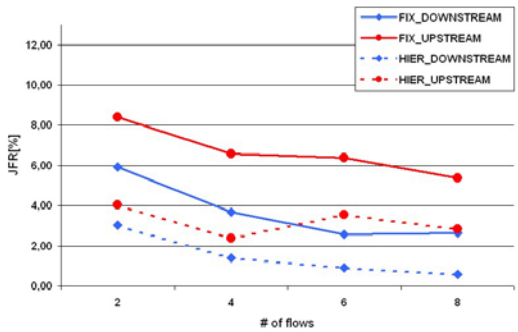

Figure 6: Job Failure Ratio (JFR)
SFSize = 6ms; CSFSize = 2.5ms

In the first case (Figure 4) the length of the parent superframe was set to 4 ms and the length of the child superframe to 1.7 ms. It can be observed that the JFR presents a decreasing tendency with the increase in the number of traffic flows. This can be attributed to the statistical multiplexing gain obtained by the numerous small bandwidth flows against the less but with huge bandwidth demand flows. Relevant performance difference between the algorithms can be seen when the number of flows is small. As the number of flows increases the performance of the two algorithms converges. A possible explanation of this observation is to attribute this phenomenon to the statistical multiplexing.

If the length of the parent superframe is increased (from 4 to 6 ms) the difference between the performance of the fixed and hierarchical algorithms will be more accentuated. In Figure 5 we can observe that the normal superframes almost in all the cases have two times higher JFR than the hierarchical ones. It is also important to notice that compared to the previous results the JFR for normal case increased, while for the hierarchical case remained around the same values. The explanation of this is that the child superframe will get its share from the channel only once for each parent superframe (6 ms instead of 4 ms), which means that its frequency was considerably decreased. Therefore, the above presented problem about the unused parts of the child respective parent superframes will be even more accentuated. This will result in a bottleneck and a higher JFR. However,

the hierarchical superframes manage to avoid this problem, since if there are packets waiting at some nodes, these can be allocated immediately in the mini superframes; thus, channel utilization will increase.
The above mentioned problem of child piconet bottleneck can be reduced if the length of its superframe is increased. The results are presented in Figure 6, where it can be seen that the normal superframes JFR values decreased considerably while in case of hierarchical superframes we obtained only a slight decrease. However, there is still considerable difference in performance between the two kinds of superframe generation algorithms, in the favor of the hierarchical algorithm.
It is also interesting to notice that there is a considerable difference between the performance of the upstream and downstream flows. The upstream flows have a higher JFR, even in the case of hierarchical superframes. This effect can be attributed to the way of internal state information signaling for the scheduler. Since the downstream traffic goes from the master towards the slave, the master knows its own internal status and based on this information it is able do schedule the downward packets. For upstream traffic the slave first signals the state information to the master. This will be done in one superframe, and only in the next superframe the upstream packets can be scheduled. Therefore, there will be underutilization of superframes in case of upstream traffic. The hierarchical superframes decrease this effect, since the presence of mini beacons allows the PNC to avoid the underutilization of the superframes.

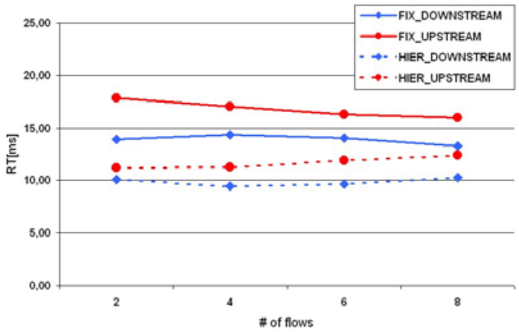

Figure 7: Response Time (RT)
SFSize = 4ms; CSFSize = 1.7ms

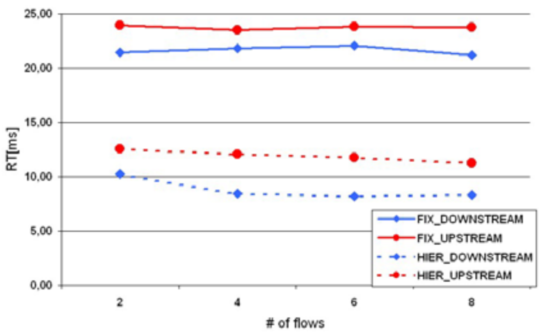

Figure 8: Response Time (RT)
SFSize = 6ms; CSFSize = 1.7ms

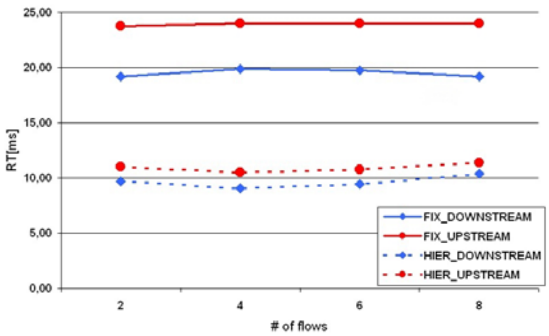

Figure 9: Response Time (RT)
SFSize = 6ms; CSFSize = 2.5ms

If Response Time (RT) is considered, similar observations can be made as in JFR case (Figure 7, Figure 8, Figure 9). In all cases the upstream traffic shows higher RT values than the downstream one. We can draw the conclusion that it is important to keep in consideration the traffic directions at the scatternet formation. On the other hand the higher the applied superframe size, the higher the value of the RT metric. This phenomenon can be assigned to the signaling delay in the piconets.
We can see that the hierarchical superframe formation decreases the RT values for both the upstream and downstream cases, which means that the performance is increased. It is almost indifferent whether we use 4 ms or 6 ms parent superframe sizes, 1.7 ms or 2.5 ms child superframe sizes; the average RT value is kept in the (8 -13) ms interval. Based on these significant observations, the behavior of the hierarchical superframe formation algorithm will be further studied since this .phenomenon is most probable in strong relation with the packet delay variation.

4.2 Investigation on large topologies

In this section we give a formal description of the optimal scatternet formation problem, formulate it as an Integer Linear Programming and give a heuristic method.

Let $G_v(\mathcal{N}_v, \mathcal{E}_v)$ denote the given *visibility grap*h with $\mathcal{N}_v$ the set of nodes and $\mathcal{E}_v$ the set of directed edges. An edge $e_{ij} \in \mathcal{E}_v$ denotes that node *j* is in the range node *i*. The output is the *scatternet graph* $G_s(\mathcal{N}_s, \mathcal{E}_s)$ with $\mathcal{N}_s$ the set of its nodes and $\mathcal{E}_s$ the set of its directed edges. Each edge in the scatternet graph is directed to a slave from its master. We assume that a slave is connected to one master. There is one master in the scatternet, which is not a slave. We call this node the *main master*.

According to the standard and our assumptions, the following statements hold:

1. The visibility graph contains the same set of nodes as the scatternet graph: $N_s = N_v$, simply denoted as $\mathcal{N}$.
2. $\mathcal{E}_s \subseteq \mathcal{E}_v$
3. $\mathcal{N}_m$, the set of masters is a subset of all nodes: $\mathcal{N}_m \subseteq \mathcal{N}$
4. G_s is a tree with the "main master" $i \in \mathcal{N}_m$ in its root.
5. The leafs of the tree are the set of slaves: $\mathcal{N}$-$\mathcal{N}_m$
6. Since a piconet contains exactly one master, we refer to the piconet through its master node *i*, $i \in \mathcal{N}$.

The problem can be formulated as an Integer Programming task. For the objective, we chose to minimize the number of piconets, but this can be changed, e.g., to maximize the network throughput. Any commercially available package can be used for solving this problem, e.g. CPLEX [11] or LP-Solve [12].

Variables.

For each node $i \in \mathcal{N}$ a binary variable μ_i is defined, which is equal to 1 if node *i* is a master and equal to 0 otherwise. Furthermore for each node $i \in \mathcal{N}$ a binary variable ν_i is defined, which is equal to 1 if node *i* is a "main master" and equal to 0 otherwise. We denote the maximum number of active slaves that can be assigned to a master by S_{MAX}.

For each edge (pair of nodes) (*i*,*j*), $i,j \in \mathcal{N}$, we define the set of assignment variables, $\mathcal{X}=\{x_{ij}\}$. The variable x_{ij} takes value 1 if *j* is assigned to master *i*, in other words it belongs to the scatternet graph:

$$x_{ij} = \begin{cases} 1 & \text{if } (i,j) \subset E_s \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Objective.

The objective is to minimize the number of masters (which equals to the number of piconets).

$$\min \sum_{i \in \mathcal{N}} \mu_i \quad (2)$$

Constraints.

Ensure that there is exactly one main master:

$$\sum_{i \in \mathcal{N}} \nu_i = 1 \quad (3)$$

Ensure that that "main master" node is a "master" node as well:

$$\nu_i \leq \mu_i \quad \forall i \in \mathcal{N} \quad (4)$$

To ensure a tree:

$$x_{ij} + x_{ji} \leq 1$$

$$\sum_{(i,j)\in\mathcal{E}_v} x_{ij} = N - 1$$

$$\sum_{i\in\mathcal{N}} x_{ij} \leq 1 - \nu_j \quad \forall j \in \mathcal{N} \qquad (5)(6)(7)$$

Limiting the number of slaves assigned to a master (and limitting the out-degree of a slave to 0):

$$\sum_{j\in\mathcal{N}} x_{ij} \leq S_{MAX}\mu_i \quad \forall i \in \mathcal{N} \qquad (8)$$

Nummerical results.

While the performance of the large scatternet formation algorithms were investigated, we have used 20 nodes dropped randomly on a 25m x 25m area. Each node has radio coverage of 10m. Considering the scatternet formation, all the above presented algorithms were applied, as well as the optimized topology. In each resulting scatternet the traffic pattern consisted from video flows. Each flow had 3 Mbps bandwidth with a burst lifetime of 133ms. The considered superframe size was set to 4 ms. The size of the child superframes were allocated based on the traffic pattern intensiveness in the piconets.
With the above considerations we have analyzed the JFR metric alteration in case of the different algorithms (see Figure 10.). As we can see on the figure, the JFR is increasing as the *limited-node algorithm* restricts the maximum number of attachable slaves to a PNC. This phenomenon is coming forward because the smaller the piconet size, the higher the number of the piconets needed to forward the packets of a flow to destination. As the used piconets number is increasing, the transmission time of packets is also increasing; packet deadline is reached, so the JFR value is increasing. We can also see on the figure that the *random* and *max-node algorithms* are presenting similar behaviors. This means that the *random algorithm*, which exhibits the most practicable approach between the algorithms, it is viable for real life scatternet formation in case of the investigated topologies.

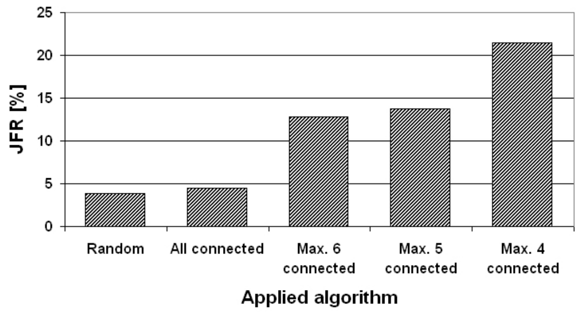

Figure 10: JFR at different alg.

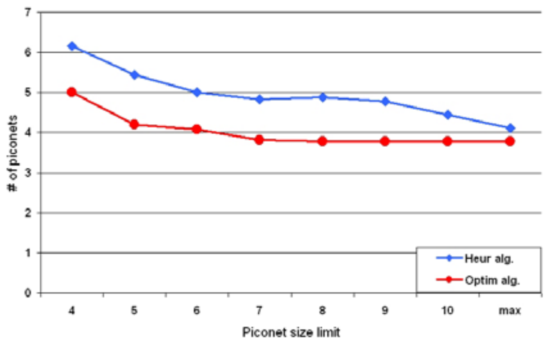

Figure 11: CPLEX vs. Limited-node alg.

We have also compared the results of CPLEX scatternet optimization with the scatternets generated by the *limited-node algorithm*. As the Figure 11 shows, the less is the number of attachable nodes to a master, the higher the difference between the *optimized* and the *heuristic (max respective limited-node) algorithms*. It can be seen that if the *max-node algorithm* is used, the difference between the optimized and the heuristic algorithms is negligible. This means, that if in real scenarios for scatternet topology construction we use the *random algorithm* we can obtain a scatternet with good approximation of the optimized one; thus, the performance of the system will be close to the theoretical algorithm.

5 Conclusions

The IEEE 802.15.3 standard and other dynamic WPANs allow the formation of scatternets in order to extend network coverage. In this paper we studied the performance implications of both small and large scatternet topologies and identified specific drawbacks of the superframe management. A hierarchical superframe based method has been proposed to avoid the detected resource wastage. Using different scatternet generation

algorithms we investigated the performance of larger scatternets as well. Our results reveal that the scatternet construction algorithm affects the network performance (e.g., throughput).
As we have shown, besides the number of consisting piconets the traffic pattern affects the scatternet performance as well. In the future we aim to investigate the scatternet optimization further, based on the applied traffic (OD matrix). Furthermore, scatternet formation will be optimized considering the energy consumption parameters of the nodes.

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