Optimal Topology Design in Wireless Personal Area Networks

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ABSTRACT

In this paper, we deal with the optimal topology design in wireless personal area networks based on the Bluetooth technology. The problem consists in determining how to connect network nodes and group them into *piconets* in such a way that the system performance is optimized. Each piconet includes one central controller, the *master*, and several nodes called *slaves*. Since one of the major issues in WPANs is energy consumption at master nodes, we select as the objective of topology optimization the time elapsing from the instant when the network starts functioning to the instant when the first master node runs out of energy. We first introduce a centralized algorithm that elects master nodes and assigns slaves to piconets; in this case, the solution that we obtain is optimal, maximizing our objective function. Then, we develop a heuristic distributed algorithm for the assignment of slaves to piconets, which is more in line with the distributed nature of the network. The performance of this distributed algorithm closely approximates the results obtained with the optimal centralized procedure.

I. INTRODUCTION

Ad-hoc wireless networks have recently experienced a wide popularity; in particular, a great deal of attention has been devoted to short-range radio systems based on the Bluetooth technology [1], [2], or, equivalently, to the IEEE 802.15 WPAN (Wireless Personal Area Network) standard [3].

WPANs operate in the Industrial, Scientific, and Medical (ISM) band at 2.4 GHz. They provide interconnection among devices that are typically battery-powered, i.e., that have limited energy resources, and have a limited transmission range (of the order of 10-30 m). The basic architectural unit in WPANs is the *piconet*, composed of a *master* device and 7 active *slave* devices at most, which can communicate with the master only. Device units are all identical and, in principle, any unit can become the master of a piconet. While there is a maximum number of active slaves allowed per piconet, an unlimited number of nodes can be part of the piconet, provided that they do not participate in the piconet transmissions [1].

A Frequency Hopping Spread Spectrum (FHSS) scheme is used at the physical level; each master chooses a different hopping sequence so that multiple piconets can operate in the same area without interfering with each other. A Time Division Duplex (TDD) technique is used to transmit and receive data in each piconet: every packet transmitted in a slot corresponds to the minimum dwell time on a frequency hop. Slots are centrally allocated by the master, and alternately used for master or slave transmissions. By using time multiplexing, nodes may participate in more than one piconet; a group of piconets in which connections between different piconets exist is called a *scatternet*, and the nodes interconnecting two or more piconets are called *bridges*.

One of the most important aspects in WPANs is the creation of the network topology, i.e., the definition of piconets, and the interconnection of the nodes deployed in the network area. Indeed, topology design has a crucial impact on the traffic load distribution within the WPAN, and on the nodes energy consumption. For instance, under the assumption that the offered traffic is uniformly distributed among the network nodes, masters are subjected to a traffic load that increases with the number of controlled slaves (masters must forward and collect the intra-piconet packets, and possibly play as bridge nodes). An erroneous choice of the number of piconets or an uneven slaves distribution among the piconets can cause 'hot spots' in the network resulting in *(i)* an inefficient use of the radio resources and *(ii)* an uneven energy consumption among masters. Moreover, the energy required for communication between a master and a slave strongly depends on the distance between the two nodes. An awkward assignment of slaves to piconets may result in high energy consumption at masters as well as slaves.

In this paper, we deal with the masters election and the assignment of the slaves to the piconets, while we do not address the election of the bridge nodes. We define an objective function to be optimized through the network topology design, which represents the above requirements on traffic load distribution and energy consumption at the network nodes. Then, we devise topology design algorithms for WPAN systems, that both maximize the objective function, and satisfy the constraints on the maximum number of active slaves allowed per piconet and on the maximum transmission range of the radio devices. While defining the objective function, we mainly focus on energy efficiency and neglect traffic quality of service (QoS) requirements. Taking into account QoS metrics, such as throughput and traffic delay, in the expression of the objective function will be subject of further research.

II. THE OBJECTIVE FUNCTION

We take as main performance metrics in WPANs the network lifetime, i.e., the time elapsing from the instant when the network starts functioning to the instant when the first piconet collapses because its master node runs out of energy.

The definition of the performance metrics considers that masters consume much more energy than slaves, because masters control all the transmissions within a piconet and (contrary to slaves, that can go to 'sleep' modes) can never move to low-power operational states.

The major contributions to power consumption in master nodes are: *(i)* the power consumed by the digital part of the device circuitry; *(ii)* the power consumed by the transceiver in transmitting and receiving mode; *(iii)* the output transmission power.

For devices that operate in the ISM bands, typical values of the power amplifier output, range over the interval $[1\ \mathrm{mW}, 20\ \mathrm{mW}]$; instead, the transceiver power consumption is of the order of tens to hundreds of mW [4]. Clearly, the output transmission power of a master depends on the radius of the corresponding piconet, and the total power consumption depends on the amount of transmitted/received/processed traffic, that is a function of the number of controlled nodes.

Under the assumption that the traffic load is uniformly distributed among the network nodes, the lifetime of the generic master i can be written as

$$L_i = \frac{E_i}{\alpha r_i^2 + \beta |n_i|} \,, \tag{1}$$

where E_i is the initial energy level at master i; r_i is the piconet radius, i.e.,the Euclidean distance between the master and the farthest node participating in the piconet; n_i is the number of nodes within the piconet, and α and β are constant weight factors. In (1), the two terms at the denominator represent the dependency of power consumption on the transmission range and on the master transmitting/receiving/processing activity, respectively. The values taken by α and β must reflect the relative weight of the two contributions to power consumption. For instance, in laptops, PDAs, or sensors based on the Bluetooth technology, the energy consumption due to output transmission power is quite significant, while it becomes almost negligible in devices where Bluetooth is the only wireless interface. Notice that, for the sake of simplicity, the relation between the master power consumption and the number of controlled nodes was assumed to be linear; however, any other type of relation could have been considered as well, with minor complexity increase.

Let $\mathcal{S}_M = \{1, \ldots, M\}$ be the set of masters; the network lifetime can be defined as

$$L = \min_{i \in \mathcal{S}_M} \{L_i\} \ . \tag{2}$$

The objective of the topology optimization is to maximize L while satisfying the following constraints:

- every node in the network must participate in one piconet at least;
- there cannot be more than 7 active slaves per piconet;
- the radius of the piconet cannot exceed a maximum value, R_{max}, that depends on the transmission capability of the radio devices.

We observe that with the proposed definition, by maximizing L we achieve both an even distribution of the traffic load over the network, and low-power communication links between masters and slaves.

III. THE NETWORK TOPOLOGY DESIGN

The problem of topology creation in WPANs can be divided into two subproblems: the election of the nodes that have to act as masters, and the assignment of the slaves to the piconets. The problem of the election of master nodes is known to be NP-hard [5]; however, heuristics can be found, which approach the optimal solution in polynomial time. In order to find the optimal solution to the two subproblems, we need to have a global knowledge of the nodes in the network and, therefore, to use centralized algorithms.

In [6], the authors presented a distributed procedure to elect a central network coordinator, that is supposed to collect information about the whole network, centrally compute the network topology, and organize the network accordingly. In this paper, initially we assume that a centralized procedure can be performed, and we find the optimal set of masters as well as the optimal assignment of slaves to piconets. Then, by maintaining the set of masters identified via the centralized algorithm, we develop a distributed assignment scheme, which well approximates the performance of the centralized solution. In fact, although an optimal network topology can be obtained through a centralized scheme only, a distributed algorithm is preferable to easily adapt the network topology to possible changes in the nodes number and position.

Finally, for the purpose of comparison, the centralized and the distributed algorithms are compared against a well known distributed assignment technique based on the minimum distance criterion [7].

A. The Centralized Algorithm

The approach we propose in order to find the optimal network topology in a centralized manner, relies on the use of the tabu search (TS) methodology [8]. Tabu search algorithms can be seen as an evolution of the classical local optimum solution search called Steepest Descent (SD). However, thanks to the TS mechanism that allows worsening solutions to be also accepted, contrary to SD, TS is not subject to local minima entrapments. TS is based on a partial exploration of the space of admissible solutions, finalized to the discovery of a good solution. The exploration starts from an initial solution that is generally obtained with a greedy algorithm and, when a stop criterion is satisfied, it returns the best visited solution.

We define as *neighborhood* the set of solutions that can be obtained from the current one by applying an appropriate transformation, called *perturbation*. At each iteration of the tabu search algorithm, all solutions in the neighborhood are evaluated and the best one is selected as the new current solution. A special rule, the *tabu list*, is introduced in order to prevent the algorithm to deterministically cycle among already visited solutions. The tabu list stores the last accepted perturbations; until a perturbation is stored in the tabu list, it cannot be used to gen-

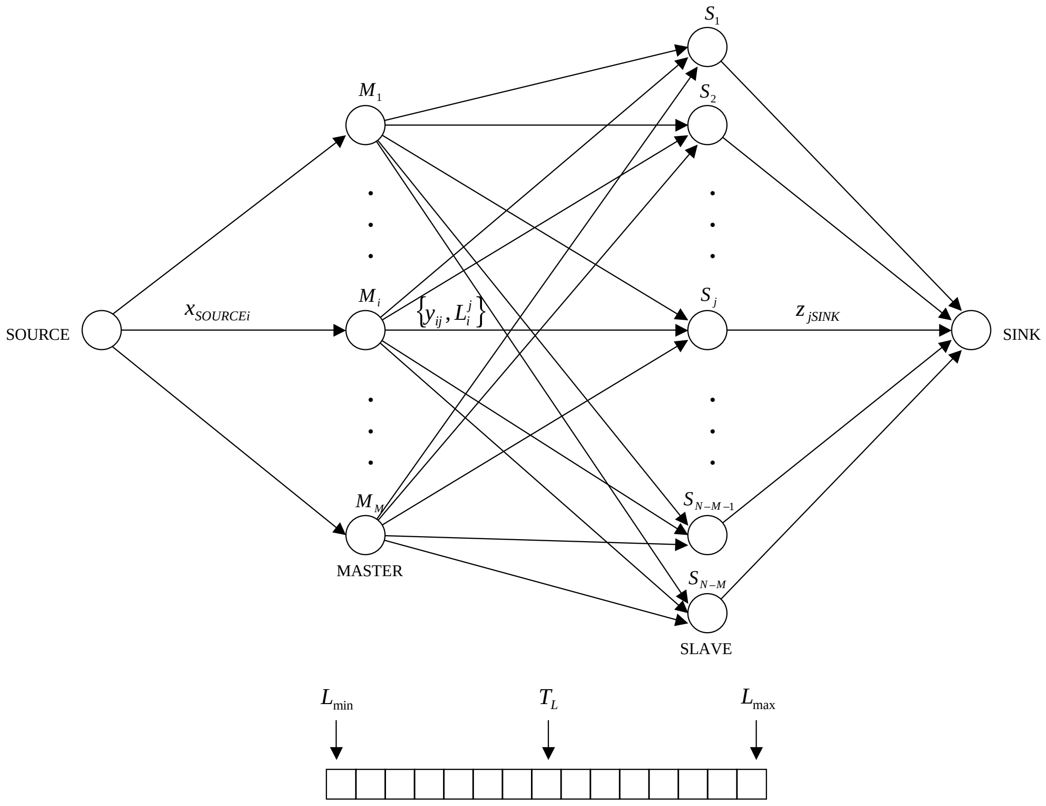

Fig. 1. Graph used in the centralized topology design algorithm.

erate a new perturbation. The choice of the tabu list size is an important factor in the optimization procedure: too small a size could cause the cyclic repetition of the same solutions, while too large a size could severely limit the number of applicable perturbations. While deriving the numerical results in Section IV, we will use as tabu list a fixed table, whose size has been properly set up to obtain a good exploration of the solutions space.

Four fundamental aspects need to be defined in TS:

- the choice of the initial solution;
- the definition of the perturbation that generates the solution neighborhood;
- the evaluation of the visited solutions;
- the stop criterion.

Let N be the number of nodes in the network and M be the number of masters, such that $M \geq N/8$. As initial solution we randomly choose the M masters among the N nodes. A perturbation is operated by changing a master with the nearest slave. Applying this perturbation to every master, we obtain the neighborhood of the current solution. Once the M masters have been selected, we execute the following algorithm to optimally assign slaves to the M piconets.

For each slave j and each master i, we compute the lifetime, denoted by L_i^j, that master i would have if its transmission range covered slave j. Observe that if the distance between master i and slave j is greater than R_{max}, L_i^j is set at 0. Then, we order the lifetime values from $L_{min} = \min_{i \in \mathcal{S}_M} L_i$ to $L_{max} = \max_{i \in \mathcal{S}_M} L_i$ and, as shown in Fig. 1, we create a graph which includes a SOURCE node, a SINK node, M MASTER nodes, and $N - M$ SLAVE nodes. The SOURCE node is connected to each of the MASTER nodes through one edge whose weight, $x_{\text{SOURCE},i}$, is equal to the number of active slaves associated with that master; $x_{\text{SOURCE},i}$ $(i = 1, \ldots, M)$ cannot be greater than 7. Each of the MASTER nodes is connected to every SLAVE node through one edge whose weight is of the form $\{y_{ij}, L_i^j\}$, where $y_{i,j}$ is equal to 1 if slave j is associated with master i and equal to 0 otherwise. Finally, each SLAVE node is connected to the SINK node through an edge with weight $z_{j,\text{SINK}}$ equal to 1 if the slave has been already assigned to a master and equal to 0 otherwise.

We fix a target lifetime value T_L, initially set at $T_L = (L_{min} + L_{max})/2$. In the graph we described, only the edges between MASTER nodes and SLAVE nodes that are associated with a value L_i^j equal to or greater than T_L are enabled, and the Ford-Fulkerson algorithm [9] is run. If an admissible solution is obtained, i.e., a solution such that $\sum_{j=1}^{N-M} z_{j,\text{SINK}} = N - M$, the value of T_L is updated to $(T_L + L_{max})/2$; otherwise, it is set equal to $(T_L + L_{min})/2$. This dicotomic procedure is repeated until an admissible solution that maximizes T_L is found.

The visited solutions are evaluated on the basis of the value of network lifetime that they provide. After a proper number of iterations, denoted by I, tabu search approaches the optimal topology for which the network lifetime is maximized. The value of I is set up in such a way that a good trade-off between the running time and the performance of the algorithm is achieved.

The complexity of the algorithm depends on the number of iterations, on the dimension of the neighborhood,

K, on the number of times the Ford-Fulkerson algorithm is repeated (i.e., $\log_2(N^2/2)$), and on the complexity of the Ford-Fulkerson algorithm (i.e., $O(MN^2)$) [9]. Thus, the overall complexity is equal to $O(IK \cdot \log N^2 \cdot MN^2)$.

B. The Distributed Assignment Algorithms

In this section we briefly outline the proposed distributed algorithm, as well as the distributed scheme based on the minimum distance criterion, that was proposed in [7]. The same set of masters found through the centralized algorithm is used, while the distributed algorithms decide the assignment of slaves to the piconets.

The Minimum Energy Assignment (MEA) algorithm. During the procedure performed by the WPAN nodes to discover their neighbors [2], nodes candidate to play the role of slaves are able to collect the following information about the masters nearby: *(i)* the energy level of the master; *(ii)* the number of slaves already under the control of the master; *(iii)* the master's transmission range. Also, by using the received signal strength indicator (RSSI), the slave is able to estimate its distance from the masters in its proximity. Based on this information, each slave can select the piconets with less than 7 active slaves, and compute the lifetime of the corresponding masters. The lifetime is calculated by considering as master's transmission range the maximum between the current piconet radius and the distance between the slave and the candidate master. The slave will join the piconet whose master presents the best value of lifetime. The complexity of the algorithm is $O(NM)$.

The Minimum Distance Assignment (MDA) algorithm [7].
During the discovering procedure that takes place in WPANs [2], each slave needs to only estimate the distance from nearby masters. The slave selects the piconets with less than 7 active slaves, and computes its distance from the selected masters. Among these, it chooses the piconet whose master is at the smallest distance. The complexity of the algorithm is $O(NM)$.

IV. NUMERICAL RESULTS

Results are presented in terms of the network lifetime that can be obtained by using the proposed algorithms, and are compared against the results produced by the MDA scheme proposed in [7]. Recall that the three procedures consider the same set of network masters, and differ in the assignment algorithm only. The solution obtained through the centralized algorithm is computed by setting the size of the tabu list to 10 and the maximum number of iterations to 100.

While deriving the results, we set the parameters α and β in (1) in such a way that the masters' power consumption due to the transmitting/receiving/processing activity is ten times greater than the transmission power contribution.

Nodes are uniformly distributed over a rectangular area and distances are normalized with respect to the diagonal dimension of the network area. R_{max} is set to be equal to one fourth of the diagonal value. The performance of the three procedures are obtained by averaging the results derived from 10 different instances of the nodes' distribution over the network area.

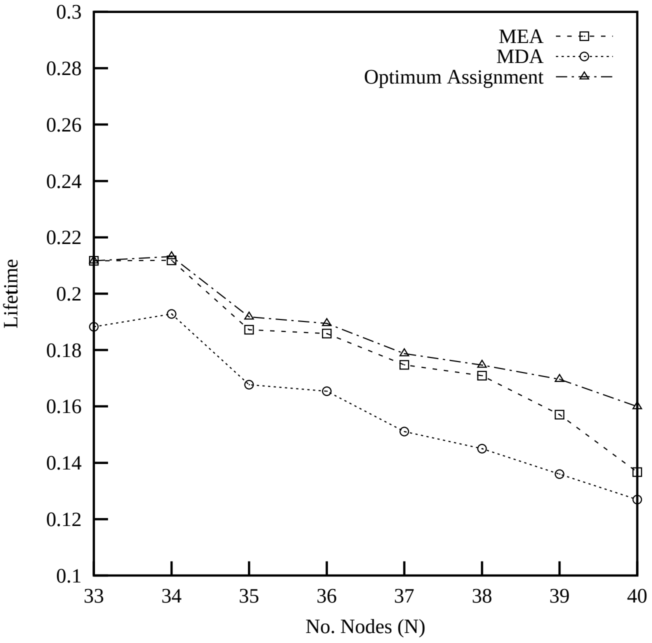

Fig. 2. Network lifetime for a number of masters equal to 5 and a varying number of nodes in the network.

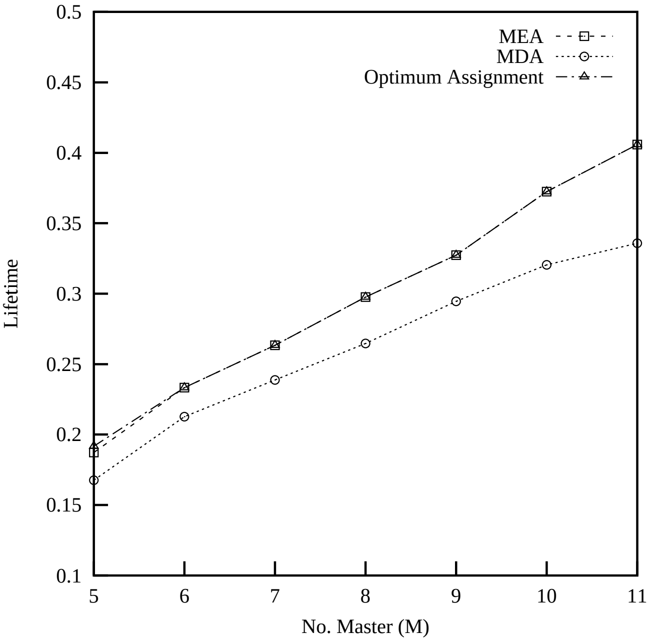

Fig. 3. Network lifetime as the number of masters varies; the number of network nodes is equal to 35.

Fig. 2 shows the network lifetime versus the number of network nodes; the number of piconets (i.e., masters) is equal to 5. As expected, the optimal assignment scheme outperforms both the MEA and the MDA algorithms; the improvement in the network lifetime that is achieved through the optimal scheme with respect to the MDA algorithm, is about 20%. From Fig. 2, it is interesting to notice that for almost any number of nodes in the network, the performance of the centralized algorithm and of the MEA algorithm are very close. The curves related to the centralized and to the MEA schemes differ only when the system is saturated, i.e., when the system consists of 40 nodes and each piconet serves 7 active slaves. This suggests that, if we fix a-priori the set of nodes that have to act as masters, the distributed MEA algorithm provides a network topology whose performance is surprisingly close to the optimal system behavior.

Now, we fix the number of network nodes to 35 and study the behavior of the network lifetime as the number of masters varies. Fig. 3 shows the results obtained when the number of masters ranges from 5 to 11, with 5 and 11 corresponding to an average number of slaves per piconet equal to 6 and 2, respectively. Observe that under these conditions, the performance of the optimal assignment and of the MEA scheme overlap, and the improvement with respect to the MDA algorithm increases as the average number of slaves per piconet decreases. In fact, for small values of M there is little variability in the assignment solution, while as M increases, the assignment based on the minimum distance criterion gives significantly worse performance. As an example, for $M = 10$, the improvement that can be achieved with the MEA scheme, with respect to the MDA algorithm, is equal to 16%.

V. CONCLUSION AND FUTURE WORK

In this paper, we addressed the problem of topology creation in WPAN systems. We defined an objective function, that is maximized through the network design procedure, as the time elapsing from the instant when the network starts functioning to the instant when the first master node runs out of energy. We proposed a centralized algorithm that both elects the network masters, and assigns slaves to piconets in an optimal way. Then, by keeping the same set of master nodes, we developed a distributed procedure for the assignment of slaves to piconets. Numerical results showed that the distributed algorithm closely approximates the performance of the centralized solution for almost any number of nodes in the network area.

Future work will focus on the performance assessment of the distributed assignment algorithm when a time-varying topology is considered and on the identification of bridge nodes between different piconets. A fundamental issue that needs to be addressed is also the trade-off between network lifetime and quality of service requirements in terms of traffic delay and throughput.

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