Gateway Placement for Latency and Energy Efficient Data Aggregation

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Abstract

The key technological constraint for sensor networks is power which is dominated by the communication component of each node. While a multi-hop communication architecture greatly decreases deployment costs and increases versatility, it also causes the communication cost between two distant nodes to be prohibitively expensive. Our goal is to demonstrate how judicious placement of a few gateway nodes at strategically selected places can significantly reduce both maximal latency and communication costs for data aggregation resulting in prolonged network lifetime and enhanced network utility.

We identify two main technical problems: gateway placement for minimizing communication delay and for minimum communication cost and establish their complexity. We have established efficient integer linear programming (ILP) formulations to optimally address these problems. Additionally, for both objectives we have developed a series of lower bound techniques and novel negative selection statistically-tuned heuristic algorithms for large instances which can not be efficiently solved by the optimal ILP formulation. We have evaluated the effectiveness of our techniques on a variety of network sizes, and statistically establish the importance of strategic gateways.

1. Introduction

Many sensor network applications such as habitat monitoring focus on data aggregation from environments which are sensitive to human-presence, hazardous, and/or distant. In these scenarios, energy conservation is critical in order to extend the lifetime of the deployed network. Recent studies indicate that communication energy dominates, by more than two orders of magnitude, computation, storage and sensing requirements for a majority of common applications [1]. It is for this reason, in this work, we focus on the strategic placement of a small number of gateways into the environment in order to both reduce power requirements as well as latency in data aggregation. While strategic placement of the network is not possible in all environments, it is applicable in areas such as national reserves. We consider the placement of gateways which are enhanced nodes that have extended (or wired) power supplies and identical or larger communication ranges than typical nodes in the network. We specifically address the problem of data aggregation, which has been shown (along with data broadcast) to comprise more than 99% of communication and therefore energy in sensor networks.

In this work, we address both the power and latency minimization problems using two optimization approaches. First, we present efficient integer linear programming (ILP) formulations for *optimal* gateway placement in smaller networks. Second, we present heuristic approaches for establishing gateway placement in networks of arbitrary size. The heuristic approach is based on a novel negative selection paradigm, where at each step the algorithm does not decide which possible positions to place a gateway at, but rather which position to exclude from consideration. The effectiveness of the heuristic algorithms is maximized using novel statistical tuning techniques without overfitting to the learning instances. The effectiveness of the techniques are demonstrated using extensive simulation and by comparing with newly developed sharp lower bound techniques for both problems.

In the next section we provide a brief overview of power management in sensor networks and gateway placement techniques. In order to be self contained in Section 3 we discuss wireless communication models and integer linear programming (ILP). In Section 4 the general approach to the gateway placement problem is presented, followed by a section on the preprocessing stage and one on the optimal ILP formulations. Section 7 presents the heuristic approaches as well as lower bound comparisons for gateway placement in large network scenarios. Finally, we conclude the work with an analysis of the proposed approaches.

2. Related Work

A number of power management methods for wireless ad-hoc network based on node sleeping strategies have been developed including: SPAN [2], ASCENT [3], GAF and STEM [4]. The focus of these efforts is on the optimization of power from the perspective of sensor node software.

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This work addresses the problem from the perspective of efficient deployment of infrastructure in order to achieve power savings. Note that these two efforts are disjoint and complementary and can be applied in conjunction.

The notion of strategically placing infrastructure to optimize cost is often referred to as the facilities location problem in graph theory. The first work to propose the use of gateways for cellular relay stations was [5]. To the best of our knowledge, the first reference which discuss the role of gateways or wired infrastructure in wireless ad-hoc networks is [6]. The key difference between this work and their research is that they propose a heuristic algorithm, and more importantly their goal is to more efficiently use pre-placed gateways, instead of optimizing the positioning of the gateways in order to minimize power consumption.

Hwang et al [7] address the problem of infrastructure or gateways in wireless networks from the perspective of the design architecture of the gateways in order to provide efficient data querying in the network. This work focuses on a 3-level hierarchical cluster of the network, while the goal here is to efficiently determine gateway positions in order to optimize both communication delay and cost.

3. Preliminaries

The delay in multi-hop networks is mainly a function of the number of communication hops, mainly because transmission is done almost at the speed of light and the main overhead is in the processing of each message at each node. Therefore, if one wants to minimize latency, the key is to minimize the number of hops from source to destination. While increasing the power level of each radio does increase transmission rate, it is not a practical solution due to the reduction in overall available bandwidth and increased power consumption [8]. The energy consumption in wireless ad-hoc networks is dominated by the radio. Therefore, the goal is to keep the radio in a low power (sleep) mode as long as possible. The most effective way to achieve this is to reduce the number of hops that each message must travel and therefore to reduce the number of radios in active modes [1].

There are several communication models in wireless networks: one-to-all, one-to-one [9], and variable angular range model. In this work, we will use a one-to-all model for simulation. In this model, the mobile nodes use omnidirectional antennas and the area to which a node can communicate is a disk centered at the node [10].

Integer linear programming (ILP) is used to specify problems where a function has to be maximized or minimized and the variables are constrained by inequality and equality constraints and/or integral restrictions on either a subset or all the variables. The objective function (OF) and the inequality or equality constraints are all linear.

$$Y = MAX(Cx) \qquad Ax \geq B \tag{1}$$

In the remainder of this work, we will specify the ILP problem in the following way. Eq. 1 specifies the objective function for the problem where we define $x = \{x_1, \cdots, x_n\}$ as 0-1 variables and C as a constant vector. The constraints of the problem can be formulated in matrix form as shown in Eq. 1, where B is a constant vector. We will denote a positive identity vector as I. In the remainder of the paper, we will use uppercase letter representation to specify constant matrices or values, and lowercase to represent variables.

4. Generic Approach Flow

In this Section, we define the process used to address the gateway placement problem. The process has three stages: preprocessing, algorithm, and postprocessing. In the preprocessing stage we assume we are given a network of deployed wireless nodes, positions and communication range known. While in the remainder of this work we will assume that the communication range for all nodes in the network is uniform and circular, this assumption is not necessary for either the ILP or heuristic approaches. The connectivity matrix of the sensor nodes in the network and a well specified communication range of the gateway nodes are required.

The two main tasks in the preprocessing phase are the identification of possible positions in the network area where the addition of gateways is useful/possible. The second task is to calculate the necessary number of communication hops for each node to communicate with each possible gateway position. The number of possible absolute positions for gateways in the network area is continuously unlimited, however the number of these positions can be reduced to a finite number through the identification of competitive regions (CRegions). We discuss identifying competitive regions in the next Section.

Once the CRegions are identified, we perform a breadth-first search from each region to each node in the network in order to determine the number of communication hops necessary to communicate between each node and a gateway placed at this position (i.e. cost for data aggregation from the sensor node to the gateway). Using the network parameters (i.e. number of nodes, connectivity between nodes, etc) and the preprocessed information, we can perform one of two optimization approaches. In the case when the network is of a reasonable size, an ILP which addresses the specified problem constraints and required optimization for the network is formulated. The ILP formulation for the problem is then solved using an off-the-shelf solver. The solution, which if found is *optimal*, will identify the CRegions in which the gateways are to be placed in order to satisfy the problem constraints. In the case of large networks, the heuristic approach is applied to determine the best gateway positions.

The final stage is the postprocessing stage, where the goal is to find the optimal position of the gateways in the selected CRegions. Note that a gateway placed at any point inside of the region has the same set of neighbors as any other point. Therefore, any point of the selected region can be used for the actual placement of a gateway. However, further optimization can be performed to minimize the distance to all neighboring nodes (i.e better communication ability). For the sake of brevity, we omit the postprocessing phase.

5. Preprocessing Stage

We have developed two preprocessing steps for the gateway placement problem in order to reduce the size and complexity of the ILP formulations. The first preprocessing step is the identification of continuous areas in the network for the placement of gateways. The second preprocessing step is the calculation of the number of communication hops for each node in the network to communicate with each potential region for gateway placement.

The identification technique is based on the disc model and is computed geometrically. For each node in the network its communication range is denoted by a circle centered at each node with radius equal to its communication range. The goal of this process is to identify all dominating regions, or *competitive regions (CRegions)*. A region is defined by overlapping communication ranges of a set of nodes. In each defined region a gateway may be placed which can communicate with the set of nodes defining the region. A region dominates a set of regions if it can also communicate with all nodes defined by the other region. In order to identify the set of CRegions, we consider each region to determine if it is a subset of another region. So, it is excluded from the competitive set.

The second preprocessing step is to calculate the number of multi-hop communications needed for each node to communicate with each identified CRegion. This is done by placing the CRegion as the root node in the network graph, where edges represent communication between nodes of the network, and performing breadth-first search. The number of communication hops for each node to each CRegion is then the breadth-first search depth of each node when the CRegion is the root of the tree.

6. Data Aggregation: Optimal ILP

In this Section, we introduce optimal ILP-based approaches for the placement of gateways into a field of deployed wireless nodes. First, we address the problem of deploying gateways into the network in order to reduce the maximal communication delay for data aggregation. Second, we introduce ILP formulations for the placement of gateways such that the energy consumption in the network is minimized.

6.1. Communication Delay

In this Subsection, we introduce two formulations for the placement of gateways into a deployed network of wireless nodes in order to reduce the communication delay of data aggregated between the sensor nodes and the gateways.

Minimization of the Number of Gateways. The goal is to determine the locations to place the minimal number of gateways into the network area under the constraint that each sensor node can communicate with at least one gateway within a given bound on the number of communication hops. As discussed in Section 4, preprocessing is performed in order to determine all possible CRegions and the communication hop count for each node to communicate to each possible CRegion. The problem can now be formulated as the set cover problem [11].

In the ILP formulation we define variable x_i where $i = 1, \ldots,$ the total number of CRegions. Binary matrix A is assigned a value of one if the hop count for each node N_j to each CRegion i is less than the specified bounds (M_{Hops}).

$$Ax \geq 1 \qquad Y = MAX(-Ix) \tag{2}$$

Using the ILP formulation, (1), the constraint is defined to ensure that each node can communication with at least one gateway within M_{Hops}. The OF minimizes the number of gateways or CRegions selected to cover all the nodes N.

Minimization of Worst-Case Delay. In the dual formulation, the goal is to place less than a specified number of gateways while minimizing the worst-case number of communication hops for any node to communicate with a gateway.

After the preprocessing phase, the problem can be formulated graph theoretically as a set of CRegions which can communicate with each node in the network with a determined number of hops. For example, consider the competitive regions to be one set of vertices and the sensor nodes in the network to be another set. Each region vertex is connected to each sensor node vertex by an edge with a weight equal to the number of hops needed for the network node to communicate with a gateway placed in that region. The goal is to select at most K region vertices such that (i) all sensor vertices are connected by at least one edge to a region vertex, (ii) the maximum edge weight over all selected connecting edges (between sensors and selected region vertices) is minimized. Each node has a selected edge which is the minimal weighted edges from each node to a selected region node. The selected edge ensures that each node is communicating with the closest selected gateway.

$$\begin{aligned} x'_i &= \text{complement value of } r_i \\ min_j &= \text{minimum hop count for node } N_j \\ m &= \text{maximum of } min_j \\ A_{ij} &= \text{number of hop counts for node } N_j \text{ to communicate to competitive region } C_i \end{aligned}$$

In order to formulate this problem as an ILP, we define four variables x, h, min and m. The variable x is a vector which specifies which CRegions are selected for gateway placement. In addition to variable x, we create a vector x' which holds the complement values of x. The complement can be calculated by the addition of the constraint,

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$x_i + x'_i = 1$ and x'_i must be a binary value. In order to determine the minimal hop count for each node to communicate with a selected gateway, the hop count for the node to communicate with each selected gateway must be determined. The variable min_j is used to specify the minimum hop count for node N_j to communicate with any selected region. Lastly, we define variable m to be the maximum hop count value of the minimal hop counts of each node to communicate with a selected gateway. In addition to the variables, we define an identity vector I and a constant matrix A_{ij} which specifies the minimum hop count for each node to communicate with each CRegion as determined in the preprocessing phase.

$$Ix \geq 1 \qquad Ix \leq K \quad (3)$$
$$(Ax)I \geq I \quad (4)$$
$$min_j \geq -A_{ij}x_i - B_{hops}x'_i \text{ for all } i,j \qquad min_j \leq 0 \quad (5)$$
$$m \leq min_j \text{ for all } j \qquad m < 0 \quad (6)$$
$$Y = MAX(Im) \quad (7)$$

We define five constraints in the ILP formulation. The first two constraints (Eq. 3), are used to enforce that at least one and no more than K CRegions are selected. Additionally, each node must be able to communicate at least one selected regions, therefore the hop count for each node to a selected gateway region must be at least one (4). Therefore the most efficient communication is achieved by having each node communicate with the closest gateway. The minimum hop count for each node to communicate with a selected gateway must be found. This is achieved through the addition of constraints (5) and (6). The final objective is to minimize the maximum of the minimal hop counts. In order to achieve this and force constraints (5) and (6) to the proper values, we define the OF as (7).

The goal is to minimize m, the maximum (minimum) hop count for all nodes, therefore we specify I to be a positive identity vector since m is already a negative value (in this case since m is a single value I is solely 1). The OF will force $|m|$ to be as large as possible, therefore causing m to be assigned the smallest negative hop count possible in (6). This conditions forces variable min_j to be equal to the smallest negative hop count, which is therefore larger than all the hop counts for node j to a CRegion (5).

Constraint (5) contains two components: the hop count for each sensor node to each selected gateway and a bounds component. The first component calculates the hop count for node j to a selected CRegion i. This first component will only be a non-zero value if the region i is selected. However if the region is not selected, it must be ensured that min_j will not be assigned a zero value. To enforce this constraint we use the second component of the constraint which specifies that in the case that the region is not selected (meaning x'_i is one) then the constraint should be assigned a value larger than the negative hop count bound. This hop count bound should be larger than the largest hop count for any node to any CRegion. One Cregion must be selected, therefore min_j will never be assigned to $-B_{Hops}$.

6.2. Network Communication

If a single gateway is placed at one end of the network the average cost for a node to communicate to the gateway will be higher than if the gateway is placed in the center of the network. In this Section, we introduce a ILP formulation for the placement of a minimum number of gateways into the network such that the total amount of communication for all nodes to communicate with a gateway is less than a specified bound.

Minimization of the Number of Gateways. The goal of this problem is the identify the minimal number of CRegions such that the sum of all the minimal communication hops for each node to a selected CRegion is less than the given bounds (M_{Hops}).

The formulation is similar to the Minimize Worst-Case Hop Problem in the previous Subsection, all variables and constants are used except m. All other constraints remain, except the second constraint in Eq. (3) which is replaced by $Imin \leq M_{Hops}$, which ensures the bounds on the total number of communication hops used. The objective is to minimize the number of gateways selected, therefore defined as $Y = MAX(-Ix)$.

Minimization of Total Communication Cost. The dual of the above problem states for a specified number of gateways, find a placement for them in such a way that the total number of communication hops needed for all sensors to communicate with the closest gateway is minimized. In order to solve this problem, the formulation for minimization of worst-case delay (Eq. 6 is removed) is used and the OF is changed to $Y = MAX(-Imin)$.

7. Data Aggregation: Large Instances

In this section we introduce lower bounds (LB) and heuristics for addressing the gateway placement problems for networks which can not be efficiently solved using ILP due to their size (number of CRegions and nodes).

All of our LBs are derived using the same methodology: we eliminate a subset of constraints from the original problem formulation and optimally solve in polynomial time the relaxed problem. There are two guiding principles when deciding which constraints should be removed from consideration. The first is that we want to transform the original computationally intractable problem into a problem of polynomial complexity which can be rapidly solved for all instances of interest in a short period of time. The second principle is that we want to keep all constraints that are essential to the formulation of the problem so that the bound is as sharp as possible.

Lower Bound: Communication Delay. We demonstrate our lower bound techniques for the placement of

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G	Covers	Util
A	{1,2,6,7}	4
B	{1,4}	2
C	{2,5,6,8}	4
D	{1,3,6,7,8}	5
E	{2,3,5}	3
F	{4,6}	2
G	{3,5,8}	3

N	Covered By	C_i
1	{A,B,D}	$\frac{1}{5}$
2	{A,C,E}	$\frac{1}{4}$
3	{D,E,G}	$\frac{1}{5}$
4	{B,F}	$\frac{1}{2}$
5	{C,E,G}	$\frac{1}{4}$
6	{A,C,D,F}	$\frac{1}{5}$
7	{A,D}	$\frac{1}{5}$
8	{C,D,G}	$\frac{1}{5}$

Table 1. Example of lower bound for delay.

gateways in such a way that all nodes are able to communicate to one of the placed gateways in no more than k hops. To formulate this technique, we identify for each node all CRegions that are within M_{Hops} distance.

For each node the minimal expected cost in the following way. The utility of a gateway is defined as the number of nodes to which the gateway can communicate. For each node i, we find the utility for each gateway which covers the node and claim that the minimum expected cost (EC_i) for the node, in terms of the number of required gateways per node, is equal to the inverse of the utility of the maximum gateway. For example, if a node is covered by three gateways with utility 7, 9, and 11 (number of nodes each CRegion can communication to), the minimal expected cost is $\frac{1}{11}$.

Consider the example set of nodes and CRegions (gateways) shown in Table 1, each gateway G covers a set of nodes N shown in column two, and the utility of each gateway is calculated. For each node N, the minimal expected cost for each gateway is calculated. It is easy to see that the lowest expected cost of the solution (i.e. number of gateways) can not be better than the sum of minimal expected costs for all nodes in the network. Of course, due to the constraint that the number of gateways must be integer, we take the ceiling of this number for the lower bound. In the case of the example, the lower bound is $\lceil \sum EC_i \rceil = 2$.

During the derivation of this LB we disregarded two types of problem constraints. The first is that a subset of the gateways may have overlapping node covers and therefore their simultaneous use will not bring benefit which is equal to the sum of individual benefits. The second disregarded type of constraints is that once we cover a particular node with a particular gateway all other nodes covered by that gateway will have the same minimal expected cost. If we reinstate the second constraint we obtain a slightly slower, but more accurate lower bound technique. This can be accomplished in the following way. We find a node with the maximal minimal expected cost. The simple but powerful observation is that all nodes covered simultaneously must have at least this cost, therefore for a node with expected cost $\frac{1}{k}$, we find a subset of $k-1$ nodes which each have as high as possible minimal expected cost and alter their cost to this higher level, dictated by the node currently with expected cost. After, we remove all of these nodes from consideration and repeatedly invoke the procedure until the all nodes are covered. At each iteration, we sum the EC of the nodes removed at the step.

The second LB relaxes the problem in such a way that it does not consider all nodes, but only a subset of nodes that can be covered simultaneously with a node that has maximal minimal expected cost. In order to further improve the sharpness of that LB and remove this limitation we have developed the third LB technique. The technique is identical to the second LB technique with one notable exception. At each step we consider for alternation of the minimal expected cost only nodes that can be simultaneously covered with one of the gateways in the set for the node with the maximal minimal expected cost.

Lower Bound: Communication Cost. Although both, placement of gateways for minimal communication delay and placement of gateways for minimal communication cost are NP-complete problems, the second problem is more difficult to address. While in the second case, communication between each node and the closest gateway in principle has different cost. Nevertheless, with a suitable modification of the LB technique from the previous Subsection can be adopted for this task. We begin by using the preprocessed number of communication hops for each node to CRegion. Next, we calculate for each potential CRegion the number of nodes that are on hop distance $1, 2, 3, \ldots, L$. At this point, we can establish a series of LBs.

The first LB is calculated by finding k gateways which have the largest number of nodes at each hop distance (breadth-first search depth). We denote the sum of the number of nodes that the gateways cover at level one as l_1, and more generally the number of nodes that the k largest of gateways covers cover at level k as k_j. We continue to add cumulatively the number $l_1, l_2, \ldots$, as long as their sum is not larger than the number of nodes in the network. In this case, the LB on the achievable number of hops is the sum of the hop count for each node to each gateway at each level l included above. No solution can have a smaller number of hops than this proposed sum due to the fact that when selecting the gateways sets at each level, the nodes in the sets are not disjoint. In order to establish a sharper bound we will address the following problem which is a relaxation of the gateway placement for minimization of communication cost. The problem is of polynomial complexity, we state it in Garey-Johnson format [11].

Problem: *BFS-based Gateway Selection for n Node Cover*
Given: *Graph G that consists of a single component and m gateways. Each gateway is connected to a subset of the nodes in G. For each node i for each gateway j the level l_{ij} is the number of the edges on the shortest path from i to j. Integer k and real number m.*
Question: *Is there a subset of gateway nodes with of at most k in such a way that at least n nodes are at average distance d from one of these selected gateways?*

Lemma: The farthest node with respect to to each of the gateways which are used to create the sum of the required number of nodes are at the same level. With respect to each selected gateway we will include all nodes to the level $(l-1)$ and some nodes (possibly 0) at level (l). Proof of this lemma can be found in [12].

Based on this observation we have developed the following algorithm that yields the optimal solution to the BFS-based Gateway Selection for n Node Cover problem in polynomial time. Denote the number of nodes with that are at level j with respect of gateway i as N_{ij} and denote that the average multi-hop distance for all nodes in this set as d_{ij}. We iteratively proceed by setting the level L_a that indicates that all nodes that form the set of nodes with this level or less are in consideration. We start from the lower level (l_1) and try to find subset of k gateways that cover a total of n nodes (where n is the number of nodes in the network). We iteratively continue to increase the average level of the overall sum until we find a solution. After each increase we consider at each level the number of nodes that are covered with the property that their average distance (d_{ij}) is at most the targeted average distance. The number of nodes covered by the k gateways with the largest number of nodes is calculated. If this sum is larger than n, the total number of nodes, the LB is (L_a), otherwise the iterative process is continued by increasing L_a.

Minimization of Maximal Communication Delay Heuristic. In this Subsection, we present a heuristic optimization algorithm for gateway placement for the minimization of maximal communication delay. The approach has two major novelties, one with respect to the employed optimization mechanism, one with respect to the objective function.

The standard approach to execute the heuristic constructive algorithm is the selection at each step of the procedure one of potential gateways to be in the final overall solution. We take the opposite strategy: at each step we decide which of the candidate gateways will be eliminated from further consideration. The intuition behind this decision is that it is often much easier to accurately choose which gateway most likely will not be well suited for the final solution. After each removal of a potential gateways from further consideration, the global picture about the value of each potential gateway to be part of the final solution becomes significantly clearer due to the fact that a large subset of nodes in the network have fewer options in terms of coverage by one of the remaining gateways. Furthermore, the most important choices are made towards the end of the optimization process when not only the number of options that have to be considered is exponentially smaller, but also when one can conduct pseudo-exhaustive search using either the branch and bound technique or the ILP approach. Since, we already have the ILP formulation, we can additionally leverage on its value for this task.

The OF for determining which candidate gateways to eliminate from further consideration at each step has four components: lower bounds, average node difficulty for coverage, greedy heuristic and randomized greedy heuristic. Each component itself has two parts: one that is calculated under the assumption that a particular candidate is not included in the solution and one that is calculated assuming that the particular gateway is included into the final solution. The two parts of each component are included in the overall OF with opposite weight signs. The average coverage of each node is calculated by finding the number of gateways that currently cover each node, C_i. If this value is high, the node will be easy to cover and vice versa if it is low. We calculate the difficulty to cover the node n_i, as $dc_i = \frac{1}{C_i^2}$. Again, the measure is calculated before and after each decision that a particular node is included and excluded from the final solution. The node is retained if its exclusion does not significantly increase the overall average coverage and its inclusion has positive impact on the same characteristics.

The third component is a greedy heuristic and selects the gateway with the highest number of covered nodes. The final measure is a randomized version of the greedy algorithm. At each step we probabilistically select a gateway for inclusion based on the coverage by the gateway. The overall OF is the weighted sum of each of two parts of all four components. Weight factors were determined experimentally.

Heuristic Algorithm for Minimization of Average Communication Cost. The algorithm for Minimization of Average Communication Cost follows exactly the structure of the procedure for Minimization of Maximal Communication Delay. In addition, to straightforward substitutions of one type of LBs with another, we change the coverage efficiency components of the OF and greedy algorithms. Details can be found in [12].

8. Experimental Analysis

In this Section, we present extensive simulation results related to the improvement of communication delay and power consumption in multi-hop ad-hoc wireless networks by the addition of a small number of gateways. Our main goal is to answer the following three questions. The first is to experimentally establish a bound on the size and com-

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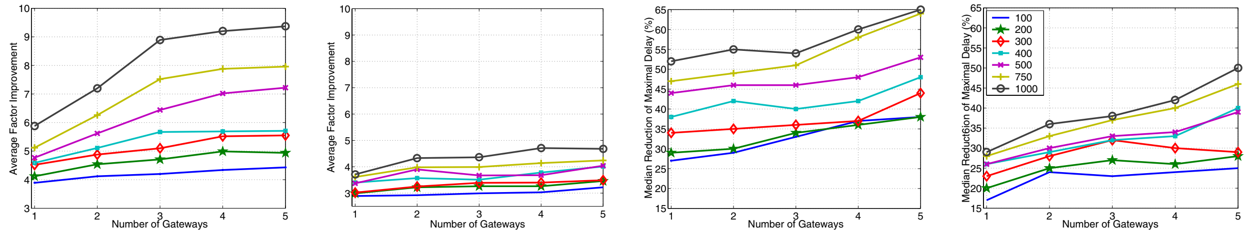
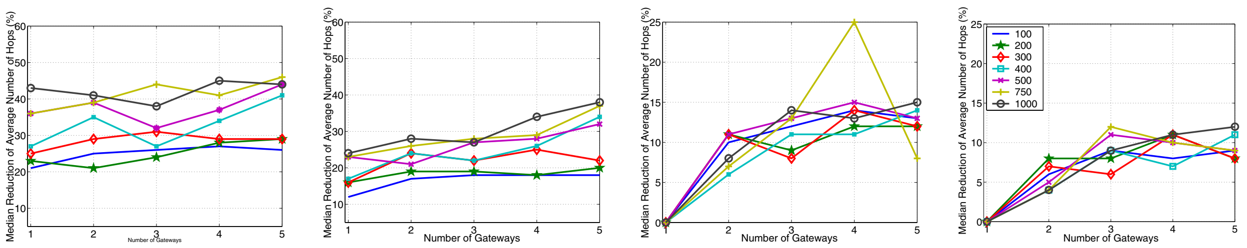


(a) Communication Range = 15m (b) Communication Range = 25m (c) Communication Range = 15m (d) Communication Range = 25m

Figure 1. (a,b) Relative effectiveness for delay reduction using heuristic vs. pseudo random gateway placement. (c,d) Median delay improvement optimized using LB heuristic over the greedy approach.



(a) Communication Range = 15m (b) Communication Range = 25m (c) Communication Range = 15m (d) Communication Range = 25m

Figure 2. (a,b) Median hop improvement for the heuristic over the greedy approach, (c,d) Median hop improvement for the LB over the heuristic approach.

plexity of the netowrk which can be optimally solved using the state-of-the-art ILP CPLEX solver. The second objective is to quantify the effectiveness of our heuristics by comparing them against greedy algorithms. The final goal is to simultaneously evaluate the effectiveness of both the heuristic algorithm and the sharpness of the LB by comparing the gap between them.

For the purpose of our experimental studies we generated instance of wireless ad-hoc networks in the following way. All nodes were placed inside of the square of size $100m$ x $100m$. In order to control the density of the network we varied two parameters: n, the number of nodes in the network and d, the communication range between two nodes. We followed the standard communication disc model for determining which node can send a message to another node in a single hop. For each node, we generated independently their x and y-coordinates using a random number generated with uniform distribution. Therefore, our graph has the structure of uniform geometric graph. The number of nodes and the communication range was varied between two boundaries. On one side, we considered only networks that form a single connected component and on the other side we considered only networks that require at least two hops for communication between at least one pair of node. These two boundary cases are natural limits for the study of multi-hop ad-hoc networks. For each setup we generated a 100 networks and used median and average aggregate statistics to convey the effectiveness of the mechanism, algorithm or LB.

Nodes	Comm Range	Gateways Delay	Gateways Hops	Comm Range	Gateways Delay	Gateways Hops
100	25m	47	22	15m	56	29
200	25m	41	14	15m	49	19
300	25m	28	5	15m	40	8
400	25m	11	1	15m	22	3
500	25m	4	-	15m	9	-

Table 2. Size and complexity of largest instances which can be solved using ILP (CPLEX).

The ILP approach guarantees the generation of an optimal solution, therefore the key question is how large and complex instances the state-of-the-art solver can solve. For this purpose, we used the CPLEX solver on a 2.4 GHz PC and allow the maximal runtime to be one hour. Table 2 shows the size and complexity of instances which can be optimally solved using the CPLEX ILP solver under the stated conditions. The first column indicates the number of nodes,

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the second the communication range, the third the necessary number of gateways to solve the maximal delay problem, and the fourth the minimum number of hops for solving the minimal energy communication problem of this size.

We first studied the impact of placing gateways as a means to minimize the maximal number of hops to the closest gateway using randomly selected positions of gateways versus the position selected by our algorithm. The position of randomly selected gateways was selected in such a way that they are never closer to each other than some number of hops. The exact number of hops was selected in such a way that the effectiveness of random placement procedure is maximized. For simulation, we first placed a gateway at a position of a randomly selected node, after that we placed a single gateway as suggested by our heuristic algorithm. Finally, we placed k gateways at positions determined by our algorithm. Fig. 1 shows the importance of using gateways for reducing maximal communication delay. On all figures the x-axis indicates the number of nodes in the network, y-axis the number of placed gateways communication range, and on the z-axis the relative improvement of one approach against another. Specifically, Figs. 1(a) and 1(b) shows on the z-axis how the average percent reduction in maximum delay for our heuristic algorithm versus the gateway placed at a random position for communication ranges of 15m and 25m. We see the improvements increase with the number of nodes and decrease with density.

Figs. 1(c) and 1(d) summarize the information about the relative performance of our heuristic and the greedy approach when applied to the networks with varying number of nodes and changing number of gateways as indicated on the x and y-axis of the figures respectively. The z-axis indicates the median reduction of the maximal delay when our algorithm is used in place of the greedy heuristic. The assumed communication range is 15m. Fig. 1(d) show the same information for communication range 25m.

In the second series of experiments we study the effectiveness of gateways for minimizing the amount of energy required to send a single message from each of the nodes to one of the gateways. We assume that each node has a certain amount of energy and that sending and receiving a single message consume a certain amount of energy. The experimental setup is exactly as described in the analysis of the previous problem. Fig. 2 shows the same analysis as for the average communication cost problem in Fig. 1.

9. Conclusion

We proposed the use of multiple gateways to significantly reduce latency and energy consumption in multi-hop wireless networks during data aggregation. We have derived efficient ILP formulations as well as a novel negative selection statistically-tuned heuristics. The heuristics are based on newly developed relaxation based lower bounds that are also used to quantify the effectiveness of the proposed heuristics. Our simulation study indicates that the use of gateways can often reduce latency and energy consumption by several times.

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