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# A shortest path tree based algorithm for relay placement in a wireless sensor network and its performance analysis ☆

Abhijit Bhattacharya *, Anurag Kumar

*Dept. of Electrical Communication Engineering, Indian Institute of Science, Bangalore 560012, India*

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ABSTRACT

In this paper, we study a problem of designing a multi-hop wireless network for interconnecting sensors (hereafter called *source* nodes) to a Base Station (BS), by deploying a minimum number of relay nodes at a subset of *given potential locations*, while meeting a quality of service (QoS) objective specified as a hop count bound for paths from the sources to the BS. The hop count bound suffices to ensure a certain probability of the data being delivered to the BS within a given maximum delay under a light traffic model. We observe that the problem is NP-Hard. For this problem, we propose a polynomial time approximation algorithm based on iteratively constructing shortest path trees and heuristically pruning away the relay nodes used until the hop count bound is violated. Results show that the algorithm performs efficiently in various randomly generated network scenarios; in over 90% of the tested scenarios, it gave solutions that were either optimal or were worse than optimal by just one relay. We then use random graph techniques to obtain, under a certain stochastic setting, an upper bound on the average case approximation ratio of a class of algorithms (including the proposed algorithm) for this problem as a function of the number of source nodes, and the hop count bound. To the best of our knowledge, the average case analysis is the first of its kind in the relay placement literature. Since the design is based on a light traffic model, we also provide simulation results (using models for the IEEE 802.15.4 physical layer and medium access control) to assess the traffic levels up to which the QoS objectives continue to be met.

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## 1. Introduction

### 1.1. Motivation and problem definition

Large industrial establishments such as refineries, power plants and electric power distribution stations typically have a large number of sensors distributed over distances of hundreds of meters from the control center. Individual wires carry the sensor readings to the control center. Recently there has been increasing interest in replacing these wireline networks with wireless packet networks [1–3]. A similar problem arises in an intrusion detection application using a fence of passive infrared (PIR) sensors [4], where the event sensed by several sensors has to be conveyed to a Base Station (BS) quickly and reliably.

The communication range of the sensing nodes is typically a few tens of meters (depending on the RF propagation characteristics of the deployment region). Therefore, usually multi-hop communication is needed to transmit

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* Corresponding author. Tel.: +91 9742485362.
*E-mail addresses:* abhijit@ece.iisc.ernet.in (A. Bhattacharya), anurag@ece.iisc.ernet.in (A. Kumar).

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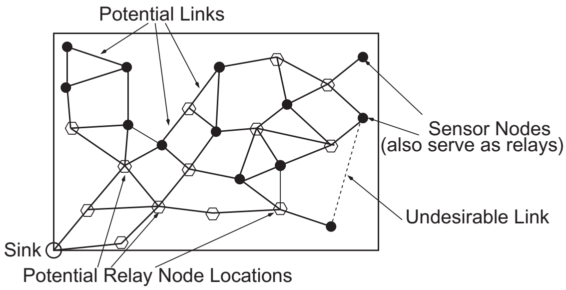


**Fig. 1.** The constrained relay placement problem; circles indicate sources, and the hexagons indicate *potential* relay locations. The edges denote the useful links between the nodes.

the sensed data to the BS. The problem that our work is aimed towards is the following:

1. There are already deployed, static sensors from which measurements, encapsulated into packets, need to be delivered to a single BS. We also refer to the sensors as *sources*.
2. Additional relays need to be placed in the region in order to provide multi-hop paths from the sources to the BS. The *sources can also act as relays* for the packets from other sources.
   In most practical applications, due to the presence of obstacles to radio propagation, or due to taboo regions, we cannot place relay nodes anywhere in the region, but only at certain designated locations. This leads to the problem of *constrained relay placement* in which the relays are constrained to be placed at certain *potential relay locations*. Furthermore, only certain links are permitted.[1] See Fig. 1 for a depiction of the problem.
3. The objective of the design is to *place as few additional relays as possible* (at the potential relay locations) while achieving a network that meets the following requirements:
   (a) There is a path from each source node to the BS; i.e., we seek a tree that spans the source nodes, and is rooted at the sink.[2]
   (b) The hop count from each source to the sink is at most $h_{\max}$.

The motivation behind such a subgraph design problem is as follows: in the context of the practical problems outlined at the beginning of this section, we are concerned with the problem of designing a QoS aware multi-hop CSMA/CA network for connecting wireless sensors with a sink, by selecting a small number of potential locations at which to place relays. In this paper we limit ourselves to the light traffic setting, which is adequate for modeling low arrival rates (say, one packet every few seconds from each source) that are typical of the so called *condition monitoring/industrial telemetry* applications. In this setting, analysis of the wireless physical layer and the medium access control used by the system (e.g., IEEE 802.15.4, which is used by Zigbee networks [6]) yields the following (see Sections 2.1 and 2.2 for a summary of the arguments):

(i) A notion of a "feasible" edge between a pair of nodes (sources or potential relays), thus yielding a graph over the sources and potential relay locations.
(ii) *A hop count bound* between each source and the sink, which *ensures a stochastic QoS objective* for packet delivery. One such objective could be that the maximum delay on any path is bounded by a given value $d_{\max}$, and the packet delivery probability (the probability of delivering a packet within the delay bound) on any path is at least $p_{del}$.

### 1.2. An overview of our contributions

In this paper we report our contributions to the subgraph design problem outlined in Section 1.1. After an extensive literature survey, we concluded that this problem of hop constrained, cost optimal network design has not yet been well studied. Although Sitanayah et al. [7,8] have proposed heuristics for this problem for general $k$, they have not made any attempt at a formal study of the complexity of the problem, or the performance guarantees of their algorithms. Very recently, Nigam and Agarwal [9] proposed a branch-and-cut algorithm to solve only a *subclass* of this problem optimally. However, even for that subclass of problems, their algorithm is not polynomial time, and hence cannot be used for large sized problem instances. Voss [10] studied a related problem of hop constrained, minimum total edge-cost network design, and proposed tabu search based heuristics for the same; but again, no formal theoretical study of either the problem, or the proposed algorithm was presented. As there is a considerable amount of relevant literature to be discussed, we have placed our detailed survey of related literature in Section 7 just before the Conclusion section.

The overall approach we take to solving the problem is the following:

1. *Approximation algorithm:* We analyze the complexity of the problem to show that the problem is NP-Hard, and develop approximation algorithms for this problem. The class of algorithms that we develop basically perform a series of shortest path computations from each source to the sink, starting with an initial feasible solution and adopting a certain combinatorial relay pruning strategy to prune relay nodes from the feasible solution sequentially; each time a relay node is pruned, a new shortest path is computed involving only the remaining nodes, while still retaining hop count feasibility. These algorithms are *simple, intuitive and fast*, and we have found that they work very well (often yielding optimal or close to optimal solutions) in our extensive numerical exploration. For brevity, we describe and analyze only one such algorithm in this paper. For other algorithms of this class, see [11].
2. *Worst case and average case analysis:* We have provided a worst case analysis of the proposed algorithm. Also, a

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[1] This could be because some links could be too long, leading to a high bit error rate and hence large packet delay, or due to an obstacle, e.g., a firewall.

[2] We have also developed algorithms for the problem where the requirement is to have at least $k > 1$ paths from each source to the BS. See [5] for details.

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