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# An approximation to the QoS aware throughput region of a tree network under IEEE 802.15.4 CSMA/CA with application to wireless sensor network design ☆

Abhijit Bhattacharya *, Anurag Kumar

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

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ABSTRACT

In the context of wireless sensor networks, we are motivated by the design of a tree network spanning a set of source nodes that generate packets, a set of additional relay nodes that only forward packets from the sources, and a data sink. We assume that the paths from the sources to the sink have bounded hop count, that the nodes use the IEEE 802.15.4 CSMA/CA for medium access control, and that there are no hidden terminals. In this setting, starting with a set of simple fixed point equations, we derive explicit conditions on the packet generation rates at the sources, so that the tree network approximately provides certain quality of service (QoS) such as end-to-end delivery probability and mean delay. The structures of our conditions provide insight on the dependence of the network performance on the arrival rate vector, *and the topological properties of the tree network*. Our numerical experiments suggest that our approximations are able to capture a significant part of the QoS aware throughput region (of a tree network), that is adequate for many sensor network applications. Furthermore, for the special case of equal arrival rates, default backoff parameters, and for a range of values of target QoS, we show that among all path-length-bounded trees (spanning a given set of sources and the data sink) that meet the conditions derived in the paper, a shortest path tree achieves the maximum throughput.



## 1. Introduction

Our work in this paper is motivated by the following broad problem of designing multi-hop ad hoc wireless networks that utilize IEEE 802.15.4 CSMA/CA as the medium access control. Given a network graph over a set of sensor nodes (also called sources), a set of potential relay locations, and a data sink (also called base station (BS)), where each link meets a certain target quality requirement, the problem is to extract from this graph, a hop length bounded[1] tree topology connecting the sensors to the BS, such that the resulting tree provides certain quality of service (QoS), typically expressed in terms of a bound on the packet delivery probability and/or on the mean packet delay, *while also achieving a large throughput region*.

As an example, consider the network graph shown in Fig. 1 over 10 sensors, 30 potential relay locations (the unlabeled vertices), and a BS at $(0,0)$; the links in the

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

[1] For a discussion of why such a hop count bound is needed, see [1,2].

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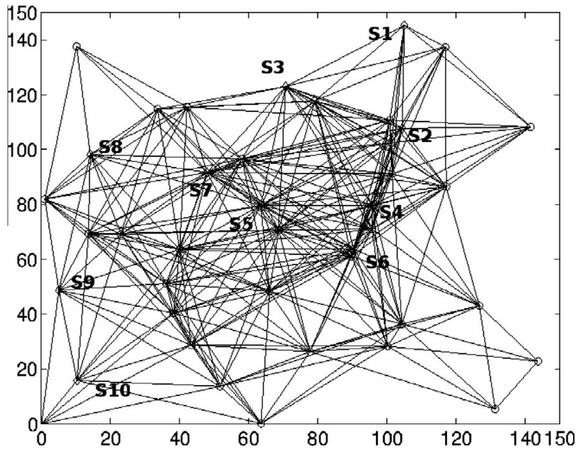


**Fig. 1.** A network graph over 10 sources (labeled $S1, S2, \ldots, S10$) and 30 potential relay locations (the unlabeled vertices); the base station (BS) is at $(0, 0)$; each edge is assumed to have a packet error rate of no more than 2%. There are no hidden nodes.

network have a worst case packet error rate of 2%. Suppose that the nodes use IEEE 802.15.4 CSMA/CA, and that all the nodes are within carrier sense range of one another. The problem is to obtain from this graph (by deploying relays at a subset of the potential locations), a tree connecting the sensors to the sink, such that the hop count from each sensor to the sink is no more than, say 5, the packet discard probability on each link is no more than 2.08%, and the mean delay on each link is no more than 20 msec (these single hop QoS requirements translate to an end-to-end delivery probability of 90%, and an end-to-end mean delay of 100 msec). In addition, among trees that meet these requirements, the resulting tree should achieve a large throughput region. The following are possible approaches for addressing such a problem.

*Via exhaustive search using simulation or an accurate performance analysis tool:* One naive way of solving the above mentioned network design problem is to consider all possible candidate tree topologies, and simulate each of them for a wide range of arrival rates to obtain their QoS respecting throughput regions, and choose the one with the largest throughput region. This method is clearly inefficient as simulation of each topology takes significant amount of time, and there could be exponentially many candidate trees (see Fig. 1). An alternative approach is to replace the simulation step with a network analysis tool (such as the one proposed in [3] for IEEE 802.15.4 CSMA/CA networks) which is considerably faster compared to simulations; however, one still requires to evaluate an exponential number of candidate trees for a wide range of arrival rates, and hence the method is still inefficient.

*Via a characterization of the QoS respecting throughput region:* A more efficient way of solving the network design problem would be to obtain an exact analytical characterization of the QoS respecting throughput region of a tree network under IEEE 802.15.4 CSMA/CA *in terms of the topological properties of the network*, and then *derive network design rules* from that characterization to maximize the throughput region. The difficulty with this approach is that for practical CSMA/CA protocols such as IEEE 802.15.4, obtaining an explicit exact characterization of the QoS respecting throughput region in terms of topological properties is notoriously hard. See Section 1.1 for more details. Therefore, some approximate methodology is in order.

*Our strategy:* Our approach in solving this problem is twofold:

1. Obtain an *explicit* approximate inner bound to the QoS respecting throughput region of a tree network in terms of the topological properties of the network, and parameters of the CSMA/CA protocol.
2. Obtain a tree that maximizes this approximate inner bound.

Such an endeavor requires performance models of general multihop wireless networks under the CSMA/CA MAC, and the derivation of design criteria from such models. In this paper, we utilize our simplification of a detailed fixed point based analysis of a multi-hop tree network operating under IEEE 802.15.4 unslotted CSMA/CA [4], provided by Srivastava et al. [3], to develop certain explicit design criteria for QoS respecting networks.

As will be explained in a later section (see Section 6), it turns out that for default protocol parameters of IEEE 802.15.4 CSMA/CA, and for a wide range of QoS targets, the resulting solution is surprisingly simple: connect each sensor to the sink using a shortest path (in terms of hop count). Although this criterion is based on an approximate inner bound to the QoS respecting throughput region, we will see in our numerical experiments that this actually achieves larger throughput than a wide range of competing topologies.

Continuing the example of Fig. 1, Fig. 2 demonstrates two different tree topologies connecting the sensors to the sink, that are both subgraphs of the example network graph of Fig. 1. The left panel shows a shortest path tree connecting the sources to the BS; this tree requires two relays. The right panel depicts a tree obtained using the SPTiRP algorithm proposed in [1] for construction of hop constrained Steiner trees with a small number of relays. In the context of this example, our results in this paper provide

i. explicit formulas for inner bounding the set of arrival rates that can be carried by either of these two topologies, while respecting the QoS objectives, and
ii. a basis for asserting that, for equal arrival rates from all sources, the shortest path tree topology in Fig. 2 will achieve the larger QoS respecting arrival rate.

Indeed, for equal arrival rates from all the sensors, it turns out (by brute force search over a wide range of arrival rates using the network analysis method presented in [3] for IEEE 802.15.4 CSMA/CA) that the shortest path tree can handle up to 5 packets/sec from each source, whereas the other tree topology in Fig. 2 can handle 3.5 packets/sec from each source. The corresponding values from our explicit inner bound formulas are obtained as 3.511 packets/sec and 2.605 packets/sec respectively. See Section 6 for details.