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Distributed multiple-message broadcast in wireless ad hoc networks under the SINR model

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ABSTRACT

In a multiple-message broadcast, an arbitrary number of messages originate at arbitrary nodes in the network at arbitrary times. The problem is to disseminate all these messages to the whole network. This paper gives the first randomized distributed multiple-message broadcast algorithm with worst-case performance guarantee in wireless ad hoc networks employing the SINR interference model which takes interferences from all the nodes in the network into account. The network model used in this paper also considers the harsh characteristics of wireless ad hoc networks: there is no prior structure, and nodes cannot perform collision detection and have little knowledge of the network topology. Under all these restrictions, our proposed randomized distributed multiple-message broadcast protocol can deliver any message m to all nodes in the network in $O(D+k+\log^2 n)$ timeslots with high probability, where D is the network diameter, k is the number of messages whose broadcasts overlap with m, and n is the number of nodes in the network. We also study the lower bound for randomized distributed multiple-message broadcast protocols. In particular, we prove that any uniform randomized algorithm needs $\Omega(D+k+\frac{\log^2 n}{\log\log\log n})$ timeslots to disseminate k messages initially stored at k nodes.

1. Introduction

In wireless networks, how to achieve efficient communications is one of the most extensively studied problems. The main challenge is to deal with interferences. Hence, the modeling of wireless interferences will play a fundamental role in the design of efficient network protocols. Previous work mostly adopted the graph based or the protocol interference model. In the graph based model, it is assumed that only nodes that are within d (a small constant) hops from a receiver can interfere with the transmission. The protocol model on the other hand assumes that a transmission can be successful if and only if there is only one transmitter within a certain range centered at the receiver. A shortcoming of these two types of models is that they treat interference as a localized phenomenon, which however is not likely the case in practice. In real wireless networks, the interference is cumulative, being contributed to by all simultaneously transmitting nodes. Because of the lack of the ability to capture the cumulative property of interference, protocols designed under the graph based or protocol model display a dramatically different performance from the expectation in practice. In this paper, we adopt the SINR model (also known as the physical interference model since it reflects the physical reality more accurately), which defines a

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global interference function and takes into account the cumulative property of interference. Besides interference, some other important features of wireless ad hoc networks should also be considered when modeling a network. For instance, when the network begins operation, no built-in infrastructure or MAC layer is available to the nodes that facilitates communication between neighboring nodes; in fact, the nodes are clueless about the network topology. Furthermore, the nodes may not be able to perform any type of collision detection because of their limited capabilities and energy as in the case of wireless sensors [16].

In the multiple-message broadcast problem, an arbitrary number of messages arrive at arbitrary nodes from the environment at arbitrary times. The problem is to deliver all these messages to all the nodes. Such a multiple-message broadcast protocol is useful as a building block in many applications including update of routing tables, topology learning of the underlying network, and aggregating functions in sensor networks.

Different from most previous work, in this work, we do not assume that all messages are initially stored at their nodes. In addition to adopting the realistic global SINR interference model, we also assume that there is no prior structure, no collision detection and nodes have little knowledge about the network topology. Under all these rigorous but practical restrictions, we present a randomized distributed multiple-message broadcast algorithm for wireless ad hoc networks, and show that, with high probability, any message m can be broadcast to all nodes in $O(D + k + \log^2 n)$ timeslots, where D is the diameter of the communication graph defined by the transmission range of nodes (refer to Section 3), k is the number of messages whose broadcast overlap with m (refer to Section 3), and n is the number of nodes in the network.[1] To the best of our knowledge, this work is the first one that studies time efficient distributed multiple-message broadcast algorithms in wireless ad hoc networks under the SINR model. Our result significantly surpasses the best known results of $\max\{O(k \log n \log \Delta + (D + n/\log n) \log n \log \Delta), O((k\Delta \log n + D) \log \Delta)\}$ [1,10] under the graph based interference model, and breaks the expected $\Omega(k + D \log(n/D))$ lower bound [4,12] for randomized solutions under the graph-based radio network model. Note that the previous results are obtained with knowledge of some network parameters being given, e.g., Δ and D; In contrast, our algorithm does not assume any prior information concerning such parameters.

Besides the proposed algorithm, we also study the lower bound of the time needed by randomized distributed algorithms to accomplish multiple-message broadcast. Specifically, we show that if all the nodes use the same transmission power, any uniform randomized algorithm in which all awaken nodes transmit a message with the same probability (independent of the communication history) in every timeslot [3] needs $\Omega(D + k + \frac{\log^2 n}{\log \log \log n})$ timeslots to accomplish multiple-message broadcast even under the assumption that all messages are initially stored at their nodes.

2. Related work

Although the SINR model (or the physical interference model) poses great challenges for designing efficient distributed algorithms due to its global interference, there have been some good attempts in recent years. In [15], with the assumption that all nodes can perform physical carrier sensing, an $O(\log n)$ time randomized distributed algorithm for computing a constant approximate dominating set was presented. The local broadcasting problem was first considered in [5]. In this paper, based on whether each node knows the number of nodes in its proximity region or not, the authors gave two randomized distributed algorithms with approximation ratios $O(\log n)$ and $O(\log^3 n)$, respectively. The latter result was improved by some recent papers [19,17], the latter of which achieves an approximation ratio of $O(\log n)$. By assuming that nodes can perform physical carrier sensing, the authors of [19] also gave two distributed deterministic local broadcasting algorithms both having an approximation ratio of $O(\log n)$ for asynchronous wake-up and synchronous wake-up scenarios. Distributed $(\Delta + 1)$-coloring (Δ is the maximum network degree) was studied in [18] and an $O(\Delta \log n + \log^2 n)$ time randomized distributed algorithm was given. There are also recent papers on finding efficient distributed algorithms for the minimum latency aggregation scheduling problem [13,14] and the wireless scheduling problem [8,6].

The multiple-message broadcast problem is also called the Many-to-All communication problem [4]. All previous work assumes the standard graph-based radio network model. In this model, there is a link existing between any pair of nodes that can communicate with each other. A transmission is successful iff there is only one neighbor transmitting a message to the receiver. Additionally, except [10,11], all work assume that all messages are stored at their nodes at the beginning of the algorithm. The authors of [1] first initiated the study of this problem. They designed a randomized algorithm accomplishing multiple-message broadcast in $O(k \log n \log \Delta + (D + n/\log n) \log n \log \Delta)$ rounds in expectation. Assuming nodes receive messages at arbitrary times from the environment, the authors of [10] proved that their modular approach can broadcast a message to all nodes in $O((k\Delta \log n + D) \log \Delta)$ rounds with high probability when there are at most k concurrent messages. How to use network coding techniques to accelerate the multiple-message broadcast has been studied in [9], in which the proposed randomized algorithm achieves a time complexity of $O(k \log \Delta + (D + \log n) \log \Delta \log n)$. All the above work assume that nodes know some or all network parameters, e.g., Δ and D. The best known lower bound for randomized solutions under the graph-based radio network model is $\Omega(k + D \log(n/D))$ in expectation [4,12]. In the paper [11], by introducing an abstract MAC layer providing reliable local broadcast communication, the authors gave a multiple-message broadcast

[1] We define the running time of a multiple-message broadcast algorithm as the maximum number of timeslots needed to disseminate any message to the whole network. If all messages are initially stored at their nodes, our defined performance measurement is equivalent to that in previous work [1], which is the number of timeslots needed to broadcast all messages to all nodes.