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Message and time efficient multi-broadcast schemes

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ABSTRACT

We consider message and time efficient broadcasting and multi-broadcasting in wireless ad-hoc networks, where a subset of nodes, each with a unique rumor, wish to broadcast their rumors to all destinations while minimizing the total number of transmissions and total time until all rumors arrive to their destination. Under centralized settings, we introduce a novel approximation algorithm that provides almost optimal results with respect to the number of transmissions and total time, separately. Later on, we show how to efficiently implement this algorithm under distributed settings, where the nodes have only local information about their surroundings. In addition, we show multiple approximation techniques based on the network collision detection capabilities and explain how to calibrate the algorithms' parameters to produce optimal results for time and messages.

1. Introduction

Data *broadcasting*, where a rumor from a single source has to be delivered to all other nodes in the graph, is considered one of the most studied problems in wireless ad-hoc networks [1]. In this paper, we study a generalized version called the *multi-broadcast* problem [2], where instead of a single source, a subset of sources $S \subseteq V$, each with a different rumor, have to deliver their rumors to *all* other nodes in the network. When S contains only a single node, the problem reduces to data *broadcasting* problem, and when S contains all the nodes, it reduces to data *gossiping* problem [3].

We use the partial aggregation model, also known as the *combined message model* [4,5], where a node can aggregate multiple messages to one by stripping message headers, using compression or correlating data from other nodes [6]. Formally, we use the compression factor c, which serves as an upper bound for the number of messages that can be compressed to a single batch; note that a message can only be compressed once. In this paper, we develop generalized algorithms which hold for any subset $S \subseteq V$ and positive integer $c \in [1, k]$, and thus suitable for both broadcasting and gossiping with and without aggregation (i.e., $c = 1$).

In data dissemination, there are two important performance metrics that directly affect the quality of the algorithm: *time* efficiency, measured by the total time until all nodes receive all rumors, and *message* efficiency, assessed by the total number of messages that are transmitted in the network. Most papers on data broadcasting and gathering concentrate on optimizing the time metric [4,7,3,8] and only provide by-product analysis of the message metric without exact performance guarantees. However, in ad-hoc networks, where the nodes have limited battery and the cost of sending a message is directly proportional to the lifetime of a node [9], minimizing the number of messages is a key aspect in the overall efficiency of

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the solution. In this work, we concentrate on finding both message and time efficient algorithms for broadcasting problem and for the more general multi-broadcasting problem, with and without aggregation. We separate our analysis to two types of network settings: *centralized* and *distributed*. In the *centralized* network setting [7], we assume that each node has full knowledge about the topology of the network, including size, distance, and the ids of all nodes. In the *distributed* network settings [10–12], we assume that each node has only partial information about the network; for example, the number of neighbors it has or the total number of nodes.

Our results. For centralized network setting we show a direct relation between messages efficiency and the size of the underlying *backbone* topology, on which rumors propagate to their destination, and show how to build a backbone such that the number of message transmitted is small. To handle time efficiency, we show how to shorten the diameter of the obtained backbone, which decreases the total time of the scheduling algorithm and ensures all rumors arrive to their destination as soon as possible. Our construction has minor impact on the message efficiency. By producing a backbone with relatively short diameter with respect to the optimal one, our results improve previous approximation ratio by Kim et al. [13]. For the distributed network settings, we first show how to construct the backbone on which rumors will propagate. Next, we show a randomized message and time efficient technique for transmitting messages using the constructed backbone structure. The technique enables calibrating the performance of the algorithm based on time or message requirements. The novelty of our approach is by comparing the quality of the proposed algorithms under each of the criteria, separately. In addition, as a by-product of our work, we present an algorithm for building a connected dominating set with short diameter with respect to the optimal.

The rest of the paper is organized as follows: in Section 2 we present the model of the network and formulate the multi-broadcast optimization problem. Summary of related work is presented in Section 3. We provide approximation algorithms for efficient message and time broadcast and multi-broadcast under centralized setting in Section 4, and extend this work for distributed setting in Section 5. Our conclusions and future work are summarized in Section 6.

2. Model and problem formulation

Ad-hoc wireless networks consist of a set of n mobile units, also called *nodes*, distributed in a two dimensional plane and equipped with radio transmitters and receivers. The power required to transmit a message from a node to distance r is $P = r^{\alpha}$, where $r \in [1, \Phi]$ is the transmission radius for some physical system parameter $\Phi > 1$ and $\alpha \in [2, 4]$ is the path loss exponent [14]. Our model is made more realistic by the incorporation of physical obstacles in the network, which represent buildings, trees or other objects that block message transmissions [15]. The transmission power of each node $P(u)$ is pre-configured, and cannot change during the course of the algorithm, and a directed edge between two nodes u and v is formed if there is no physical obstacle and if the Euclidean distance between them, $d(u, v)$ is less than $\sqrt[\alpha]{P_u}$. In addition, we also consider the special case of Unit Disc Graphs (UDG), where $P(u)$ is equal for all nodes.

Let $k \in \{1, \ldots, n\}$ be the number of different rumors in the network. In our model, the cost of sending a rumor from a node to its neighbors is fixed, but up to c rumors, $1 \le c \le k$, can be compressed to a single message, which we refer to as *batch*. Intermediate nodes can merge multiple batches, but once a batch size exceeds c original messages, it cannot be further compressed. We consider the following parameters of the network graph G: its diameter, d_G, the degree of each node $\delta(v)_G$, its maximum degree Δ_G and $h_G(u, v)$, the shortest number of hops needed to route a message from u to v in G; subscript G is removed when it is clear from the context.

In this paper, we study the *Multi_Broadcast* problem, which is defined as follows:

Input: Graph $G = (V, E)$, set S of k source nodes each with one rumor, and compression parameter $c \le k$.
Output: Multi-broadcast schedule from all nodes in S to all nodes in V.

For abbreviation we use *Broadcast* when $k = 1$ and *Multi_Broadcast* otherwise. Note that in some related work [4,7], when $k = n$ the problem is refereed to as gossiping.

We are looking for a solution to the problem under the following optimization criterion:

Message efficiency: The objective here is to minimize the number of messages transmitted in the network in the course of the algorithm. When analyzing *only* the message efficiency criteria, we do not take interferences into consideration, assuming that all messages can be scheduled by some interference-free protocol without increasing the number of messages sent (e.g., we can partition time into n time slots, and let node i transmit in time slot numbered $t = i \bmod n$). This assumption is removed when additional optimization criterion are considered. We define m_{opt} as the minimum number of messages that are transmitted in the network during the execution of the optimal solution.

Time efficiency: The objective here is to minimize the time it takes until all rumors are received by all nodes. When analyzing time efficiency, we adopt the *protocol interference model* [16], where a communication between nodes u and v is successful if no neighbor of v (the receiver) is simultaneously transmitting. For any subgraph $T \subseteq G$, let $I_p(u, T)$ be the *conflict set* of u in T, which consists of nodes that cannot be scheduled to transmit simultaneously with u because they interfere to u's recipients. Note that since we use omni-directional antennas we have $|I_p(v, T)| \le \Delta_T(\Delta_T - 1)$. We define s_{opt} as the minimum time required to deliver all rumors to their destinations.