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Latency-optimal communication in wireless mesh networks ☆

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ABSTRACT

Wireless mesh networking is an emerging communication paradigm to enable resilient, cost-efficient and reliable services for the future-generation wireless networks. We study the minimum-latency communication primitive of gossiping (all-to-all communication) in known topology Wireless Mesh Networks (WMNs), i.e., where the schedule of transmissions is pre-computed in advance based on full knowledge about the size and the topology of the WMN. Each mesh node in the WMN is initially given a message and the objective is to design a minimum-latency schedule such that each mesh node distributes its message to all other mesh nodes. The problem of computing a minimum-latency gossiping schedule for a given WMN is NP-hard, hence it is only possible to get a polynomial approximation algorithm. In this paper, we show a deterministic approximation algorithm that can complete gossiping task in $O(D + \frac{\Delta \log n}{\log \Delta})$ time units in any WMN of size n, diameter D, and maximum degree Δ. This is an asymptotically optimal schedule in the sense that there exists a WMN topology, specifically a Δ-regular tree, in which the gossiping task cannot be accomplished in less than $\Omega(D + \frac{\Delta \log n}{\log \Delta})$ units of time. Our algorithm also improves on currently best known gossiping schedule of length $O(D + \frac{\Delta \log n}{\log \Delta - \log\log n})$ (Cicalese et al. (2009) [4]).

1. Introduction

Wireless Mesh Networking (WMN) is a highly promising network architecture to converge the future-generation wireless networks. A WMN has the dynamic self-organization, self-configuration and self-healing characteristics; and additionally inherent flexibility, scalability and reliability advantages. In a WMN, the mesh nodes can communicate with each other via multi-hop routing or forwarding [1]. There are two types of WMN with respect to the mobility property, i.e. static mesh networks and mobile mesh networks. The IEEE 802.11s mesh networks in Wireless Local Area Networks (WirelessLAN) is a kind of WMN with static mesh nodes, where the Access Points (APs) can communicate with each other via multi-hop routing. Another example can be the WMN constructed by the mesh routers with static topology. If the mesh nodes are

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equipped in different moving objects, e.g. bicycles, buses and trains, the network can be a kind of WMN with mobile mesh nodes. In this paper, we focus on the WMN with static mesh nodes.

We consider the following model of a WMN: an undirected connected graph $G=(V,E)$, where V represents the set of mesh nodes of the WMN and E contains unordered pairs of distinct mesh nodes, such that $(v,w)\in E$ iff the transmissions of mesh node v can directly reach mesh node w and vice versa (the reachability of transmissions is assumed to be a symmetric relation). In this case, we say that the mesh nodes v and w are *neighbors* in G. Note that in a WMN, a message transmitted by a mesh node is always potentially sent to all of its neighbors, which is the nature and advantage of wireless communication.

The *degree* of a mesh node is the number of its neighbors. We use Δ to denote the *maximum degree* of the WMN, i.e., the maximum degree of any mesh node in the WMN. The *size of the network* is the number of mesh nodes $n=|V|$.

Communication in the WMN is synchronous and consists of a sequence of communication steps. In each step, a mesh node v either transmits or listens. If v transmits, then the transmitted message reaches each of its neighbors by the end of this step. However, a mesh node w adjacent to v successfully receives this message if and only if in this step w is listening and v is the only transmitting mesh node among w's neighbors. If mesh node w is adjacent to a transmitting mesh node but it is not listening, or it is adjacent to more than one transmitting mesh nodes, then a *collision* occurs and w does not retrieve any message in this step. Moreover, we assume that the collision is indistinguishable from the background noise (that is, the mesh nodes do not have a collision detection mechanism). Dealing with collisions is one of the main challenges in efficient wireless communication.

The two classical problems of information dissemination in the WMNs are the *broadcasting* problem and the *gossiping* problem. The broadcasting problem requires distributing a particular message from a distinguished *source* node to all other mesh nodes in the WMN. In the gossiping problem, each mesh node v in the network initially holds a message m_v, and the aim is to distribute all messages to all mesh nodes. For both problems, the minimization of the time needed to complete the task that is typically considered as the efficiency criterion.

In the model considered here, the length of a communication schedule is determined by the number of time steps required to complete the communication task. This means that we do not account for any internal computation within individual mesh nodes. Moreover, no limit is placed on the length of a message that one mesh node can transmit in one step. However, this assumption can be dropped by using the pipeline approaches proposed in [13].

Our schemes rely on the assumption that the communication algorithm can use complete information about the WMN topology. Such an assumption is acceptable since we investigate the communication scenarios in static wireless mesh networks here. Such topology-based communication algorithms are useful whenever the underlying WMN has a fairly stable topology/infrastructure. As long as no changes occur in the WMN topology during the execution of the algorithm, the tasks of broadcasting and gossiping will be completed successfully. Here, we shall not touch upon reliability issues.

Our results Computing a minimum-latency gossiping schedule is NP-hard, hence it is only possible to achieve a polynomial approximation algorithm. In this paper, we propose an (efficiently computable) deterministic approximation schedule that uses $O(D+\frac{\Delta\log n}{\log\Delta})$ time units to complete the gossiping task in any WMN of size n, diameter D, and maximum degree Δ. This is an asymptotically optimal schedule in the sense that there exists a WMN topology, specifically a Δ-regular tree, in which the gossiping task cannot be accomplished in less than $\Omega(D+\frac{\Delta\log n}{\log\Delta})$ units of time. Our scheme also improves on currently best known gossiping schedule of length $O(D+\frac{\Delta\log n}{\log\Delta-\log\log n})$ in [4].

Related work The work on communication in known topology wireless networks was initiated in the context of the broadcasting problem. In [5], Chlamtac and Weinstein prove that the broadcasting task can be completed in time $O(D\log^2 n)$ for every n-vertex wireless network of diameter D. An $\Omega(\log^2 n)$ time lower bound was proved for the family of graphs of radius 2 by Alon et al. [2]. In [6], Elkin and Kortsarz give an efficient deterministic construction of a broadcasting schedule of length $D+O(\log^4 n)$ together with a $D+O(\log^3 n)$ schedule for planar graphs. Recently, Gąsieniec, Peleg, and Xin [9] showed that a $D+O(\log^3 n)$ schedule exists for the broadcast task, that works in *any* wireless network. In the same paper, the authors also provide an optimal randomized broadcasting schedule of length $D+O(\log^2 n)$ and a new broadcasting schedule using fewer than $3D$ time slots on planar graphs. A $D+O(\log n)$-time broadcasting schedule for planar graphs has been showed in [12] by Manne, Wang, and Xin. Very recently, an $O(D+\log^2 n)$ time deterministic broadcasting schedule for any wireless network was proposed by Kowalski and Pelc in [10]. This is asymptotically optimal unless $NP\subseteq BPTIME(n^{\mathcal{O}(\log\log n)})$ [10]. Nonetheless, for large D, in [4], a $D+O(\frac{\log^3 n}{\log\log n})$ time broadcasting scheme outperforms the one in [10], because of the larger coefficient of the D term hidden in the asymptotic notation describing the time evaluation of this latter scheme. It is known that the computation of an optimal broadcast schedule is NP-hard [11], even if the underlying graph is embedded in the plane [3,14].

Gossiping in wireless networks with known topology was first studied in the context of the communication with messages of limited size, by Gąsieniec and Potapov in [7]. They proposed several optimal or close to optimal $O(n)$-time gossiping procedures for various standard wireless network topologies, including lines, rings, stars and free trees. In the same paper, an $O(n\log^2 n)$ gossiping scheme for general wireless network topology is provided and it is proved that there exists a wireless network topology in which the gossiping (with unit size messages) requires $\Omega(n\log n)$ time. In [13], Manne and Xin show the optimality of this bound by providing an $O(n\log n)$-time gossiping schedule with unit size messages in any