Ad Hoc Networks 11 (2013) 1193–1201

Contents lists available at SciVerse ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Energy efficient networking via dynamic relay node selection in wireless networks

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ARTICLE INFO

Article history:
Received 7 April 2012
Received in revised form 21 December 2012
Accepted 3 January 2013
Available online 19 January 2013

Keywords:
Network lifetime
Ad hoc networks
Average case analysis
Random graphs

ABSTRACT

Mobile wireless ad hoc networks need to maximize their network lifetime (defined as the time until the first node runs out of energy). In the broadcast network lifetime problem, all nodes are sending broadcast traffic, and one asks for an assignment of transmit powers to nodes, and for sets of relay nodes so that the network lifetime is maximized. The selection of a dynamic relay set consisting of a single node (the 'master'), can be regarded as a special case, providing lower bounds to the optimal lifetime in the general setting. This paper provides a preliminary analysis of such a 'dynamic master selection' algorithm, comparing relaying to direct routing.

1. Introduction

The finite amount of battery energy in sensor- or ad hoc networks gives rise to a number of issues concerning energy saving at the physical, MAC and network layers. Indeed, for such networks it is important to maximize the network lifetime. Here, the network lifetime is defined as the time until the first node runs out of energy. The broadcast network lifetime problem asks for settings of transmit powers and (node-dependent) sets of relay nodes, that maximize the network lifetime, while other nodes originate broadcast traffic. If we do not consider the node dependencies, we can ask for a fixed *set* of relay nodes to maximize the network lifetime, while allowing transmissions from multiple sources. This leads to lower bounds for the general network lifetime problem. This paper presents a preliminary analysis of a special case in this setting, where we ask for a *single* relay node (the 'master'), which is allowed to change over time. We compare this dynamic master selection to a direct routing approach (without multihop communication). This is of interest for ad hoc networks and sensor networks. Here one could envisage a distinction between very simple devices (clients), and more powerful devices (eligible masters). Implementing a dynamic master selection algorithm imposes little memory requirements while enhancing the relaying capabilities, and increasing network lifetime. Motivated by the fact that communication is a much more energy expensive tasks than data processing (see e.g. [1]), we focus on the efficiency of the distance-dominated communication related power consumption.

Section 2 of this paper presents an overview of related literature. Section 3 introduces the model and notation. In Section 4 of this paper we provide an approximate analysis of this problem, in a non-geometric setting, where the transmit power thresholds are randomly chosen in the unit interval. In Section 5 we address a geometric setting, where nodes are randomly distributed in the plane. There we distinguish two cases: the case where transmit power levels can be adjusted continuously, and the case where only a discrete set of transmit power levels is supported. Section 6 presents the conclusions.

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1570-8705/$ - see front matter
http://dx.doi.org/10.1016/j.adhoc.2013.01.003

2. Literature overview

Considerable research efforts in the literature attempt to reduce energy consumption and maximize the network lifetime for ad hoc and wireless sensor networks. In [2] a general overview of strategies to alleviate power consumption in wireless networks is presented. It is natural to use power control to reduce the transmission power and thus minimize the energy consumption at the physical layer [3]. In the context of mobile ad hoc networks (MANETs), the complexity is reduced by assuming transmissions originate from a single source ([4–6]). The related problem of minimizing the total energy consumption for broadcast traffic has also been widely studied, because it provides a crude upper bound to the lifetime of the network. In [7,8] it is shown that minimizing the total transmit power is NP-hard. A general approximation framework for fault tolerant topology control problems is developed in [9]. However, this problem does not address the residual energy of the nodes.

There is also work focusing on selection of multihop routes in order to maximize the network lifetime. In [10] a new routing algorithm is proposed in terms of maximizing the system lifetime, which can also be interpreted as maximizing the amount of information transfer between origin and destination given the limited energy. In [3] this approach is further extended to take into account Shannon capacity of each link. Addressing the heterogeneous case, where nodes run on batteries or are connected to the mains is [11], where a new energy- aware routing algorithm is developed. These approaches typically address unicast traffic over a multihop network, whereas we address broadcast traffic in a single hop situation. When the locations of part of the nodes are a variable, the problem is to find the (energy-optimal) location of relay nodes, given the location of the sensors within the network, this problem is for example studied in [12] and in [13].

The work in this paper is closest related to the research on hierarchical routing protocols for sensor networks. This involves the partitioning of nodes into a number of small groups called clusters. The member nodes send their data to their immediate cluster heads (corresponding to our master). These perform data aggregation and send the message to the next destination. As discussed in [14,15], LEACH (Low Energy Adaptive Clustering Hierarchy) is perhaps the first cluster based routing protocol for wireless sensor networks, which uses a stochastic model for cluster head selection. This protocol forms clusters by using a distributed stochastic algorithm. However, LEACH does not take residual energy into account. In [16], an energy efficient cluster head (EECHE) selection algorithm is proposed, by adjusting the threshold (determining the likelihood of cluster head selection) based on the residual energy. The algorithm of [17], focuses on minimizing the number of communication messages. The problem of finding the optimal path for data transmission between cluster heads and the base station is addressed in [18].

The main contribution of this paper is that we do not target a *single (unicast) destination* (the base station), but that in our case the master (cluster head) should broadcast the data to *all* nodes. Moreover, the algorithm we propose is not stochastic but deterministic in nature, and takes residual energy explicitly into account. In addition, we complement the simulation results on the algorithm with a formal analysis. We believe the analytical method as presented here could be used to analyze the various clustering algorithms as well.

3. General model and notation

In order to formally define the problem, we introduce some notation. For a set V (denoting the potential master nodes), a power assignment is a function $p : V \to \mathbb{R}$. To each ordered pair (u, v) of transceivers we assign a transmit power threshold, denoted by $c(u, v)$, with the following meaning: a signal transmitted by u can be received by v only when the transmit power is at least $c(u, v)$. We assume that the $c(u, v)$ can be determined, and that these are symmetric. A node can only be chosen a master if it can reach all other nodes when transmitting at maximum power. In our analysis, we only consider those nodes that are eligible as master, i.e., those nodes that can reach all other nodes when transmitting at maximum power. For a node $m \in V$, let p_m denote the power assignment $p_m : V \to \mathbb{R}$ defined as:

$$p_m(v) = \begin{cases} c(v,m) & \text{for } v \neq m, \\ \max_{v\in V} c(v,m) & \text{for } v = m. \end{cases} \tag{1}$$

$p_m(v)$ can be interpreted as the power assigned to $v$when m is master.

In [11,13] and (and references herein), the power consumption due to transmission of a packet consists of a distance independent part for transmission and reception (due to activation of transmitter and receiver circuits) and a distance related part for transmission. In this paper, we focus on the efficiency of the distance-dominated communication related power consumption, assuming a linear battery model. So, each vertex is equipped with battery supply b_v, which is reduced by amount $\lambda p_m(v)$ for each message transmission by v with transmit power $p_m(v)$. However, the analysis presented abovecan be extended to case of more complicated power models.

We assume that all nodes $v \in V$ transmit at a constant rate a_v, where a_v denote the number of messages per time unit. We call a series of transmissions were each node $v \in V$ transmits a_v times a *round*. With these assumptions, we obtain for the battery reduction after one round (with master node m):

$$b_v = \begin{cases} b_m - \lambda p_m(v) \sum_{v\in V} a_v & \text{for } v = m, \\ b_v - \lambda a_v p_m(v) & \text{for } v \neq m. \end{cases}$$

In [19] we analyzed the case where a master m is kept constant for the whole lifetime of the network. This paper is concerned with a dynamic version of this problem: given a graph $G = (V, E, c, b, a)$, where $c : E \to \mathbb{R}$ denotes the transmit power thresholds, and $b : V \to \mathbb{R}$ denotes the initial battery levels b_v, $v \in V$, and the relative frequencies $a_1, \ldots, a_n$. We ask for the number of rounds x_v for each node v to be master. Here, the $x_v \geqslant 0$ have to be chosen in such a way that $\sum_{v\in V} x_v$ is maximized under the condition that the remaining battery capacity of each node is positive during the lifetime of the network. Here, x denotes the vector $(x_1, \ldots, x_n)$. Corre-