Ad Hoc Networks 18 (2014) 40–54

Contents lists available at SciVerse ScienceDirect

Ad Hoc Networks

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

# Analysis of energy efficient distributed neighbour discovery mechanisms for Machine-to-Machine Networks

F. Vázquez-Gallego [a,*], J. Alonso-Zarate [a], L. Alonso [b], M. Dohler [a]

[a] Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Parc Mediterrani de la Tecnologia (PMT), Av., Carl Friedrich Gauss 7, 08860 Castelldefels, Barcelona, Spain

[b] Department of Signal Theory and Communications, Universitat Politècnica de Catalunya (UPC), EETAC – BarcelonaTECH, 08860 Castelldefels, Barcelona, Spain

ARTICLE INFO

*Article history:*
Received 25 January 2013
Accepted 16 March 2013
Available online 26 March 2013

*Keywords:*
Cooperative
Distributed
Discovery
Frame slotted-ALOHA
Contention tree
Energy
Delay

ABSTRACT

Energy efficiency is one of the main challenges of Machine-to-Machine (M2M) networks, since they aim at connecting devices with limited access to power sources and operate without human intervention. It has been shown in the past that the use of short-range cooperation between wireless devices equipped with multiple Radio Access Technologies (RATs) can achieve energy savings and extend the lifetime of cellular wireless networks. Devices with cellular connectivity can become temporary gateways to provide energy-constrained devices within the short-range cluster with access to the long range cellular infrastructure. To this end, the devices need to discover their neighbours using their short-range radio interface to identify and select potential gateway candidates. Existing neighbour discovery mechanisms perform poorly in terms of delay and energy consumption to maintain, continuously at each device, complete neighbourhood information, and thus may not be suitable for energy-constrained M2M networks. In this paper, we focus on distributed neighbour discovery mechanisms that are initiated dynamically and spontaneously by a single device to discover only its single-hop neighbours. We formulate accurate delay and energy models of three discovery mechanisms based on frame slotted-ALOHA and contention tree algorithms, and compare their performance in terms of delay and energy consumption.



## 1. Introduction

Once deployed, a Machine to Machine (M2M) network must operate autonomously for years or even decades without human intervention. To this end, energy efficiency is a must in the design of such communication networks. It has been shown in the past that the cooperation between long-range and short-range communication interfaces can help to improve the energy efficiency of communications [1]. In this paper, we consider the situation where some devices are equipped with two radio interfaces (one for cellular networks and another for short-range networks) and can cooperate with close neighbours in the short-range by acting as dynamic gateways and provide them with cellular connectivity. This is aligned with the hybrid M2M architecture envisioned by ETSI, where Local Area M2M Networks will cooperate with wide-area networks through the use of M2M Gateways to provide ubiquitous coverage to M2M devices [2,3]. In this paper, we focus on the challenge that arises when a single short-range radio device needs cellular connectivity and needs to discover the neighbour devices in its single-hop range that can act as M2M gateway.

There are a large number of neighbour discovery mechanisms [4–10] which aim at maintaining continuously and locally at each device the complete information of its single-hop neighbourhood. This information typically includes a list of the identifiers of all the devices and a measure of the channel conditions of the device-to-device

* Corresponding author.
*E-mail address:* francisco.vazquez@cttc.es (F. Vázquez-Gallego).

1570-8705/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.adhoc.2013.03.006

radio links. However, these mechanisms are inefficient in terms of delay and energy consumption due to the following facts:

(1) All the devices in the network have to transmit their identification repeatedly until the discovery process terminates.
(2) The devices have to switch between 'transmission' and 'listening' modes so that each device can hear every neighbour for at least once.
(3) The process has to be executed periodically in order to adapt to the network topology changes caused by devices' mobility and failure.
(4) In most cases, the devices need an estimation of the size of the neighbourhood so that each device can determine when to terminate the process.

Therefore, conventional neighbour discovery mechanisms may not be optimal for delay- and energy-constrained M2M networks. This is the main motivation for the work presented in this paper, where we focus on distributed neighbour discovery mechanisms that are initiated by a single device to identify only those neighbours within its transmission range using the short-range radio interface. The discovery process is executed dynamically and spontaneously in a distributed manner. This approach is similar to Radio Frequency Identification (RFID) [12], where a reader transmits requests to the tags and they respond with their identification. Since the number of devices can be large, a Medium Access Control (MAC) protocol is needed to resolve the contention between devices that may transmit simultaneously. Two types of MAC protocols are typically implemented in RFID applications: (i) based on frame slotted (FS)-ALOHA, and (ii) based on tree-splitting, i.e., contention tree algorithm [20], that organise the tags into smaller sub-groups to reduce the number of collisions.

As discussed in more details later in Section 2, previous works in RFID mainly focus on the minimization of the delay to identify the full set of tags, but do not describe how to minimize the energy consumed by the reader and the tags during the identification process. In addition, existing delay and energy models in RFID contain several simplifications which make them not adequate for M2M wireless networks; e.g., the authors consider only the energy consumed by the tags in transmission, but neither in reception nor in sleep states.

In this paper, we aim to fill this gap with two main contributions:

(1) We formulate accurate delay and energy models for three distributed neighbour discovery mechanisms based on: *(i)* two variants of FS-ALOHA and *(ii)* a contention tree algorithm. A preliminary description of the energy model for the FS-ALOHA algorithms was already presented in [11].
(2) We perform extensive evaluation in order to compare the performance of these mechanisms and determine how to minimize the delay and energy consumption. For this purpose, we consider radio transceivers in compliance with the IEEE 802.15.4 standard [27].

The remainder of this paper is organised as follows. In Section 2, we describe the related work to motivate the contribution presented in this paper. In Section 3, we present the system model and the distributed neighbour discovery mechanisms based on FS-ALOHA and the contention tree algorithm. In Section 4 and Section 5, we present the probabilistic analysis of FS-ALOHA and the contention tree algorithm, respectively. Section 6 is devoted to the formulation of the delay and energy models. In Section 7, we validate the models through computer simulation and discuss the results. Finally, Section 8 concludes the paper.

## 2. Related work

In this section, we describe the related work for the two categories of MAC protocols typically used in RFID systems.

### 2.1. Frame slotted-ALOHA

In FS-ALOHA [13], each request for identification is followed by a time frame divided into slots. Each tag chooses one of the slots of the frame randomly in order to transmit its identification. The process is repeated, frame after frame, until the reader has decoded the identification of all the tags. A number of research works in RFID have analysed the performance of FS-ALOHA in terms of average delay and energy consumption.

Regarding performance in terms of delay, the work in [14] has computed the optimal frame length (i.e., the number of access slots per frame), for different numbers of tags, that reduces the number of frames required to identify all the tags. This work assumes that the number of contending tags is known a priori and is constant during the identification process. The number of frames needed to identify all the tags has been calculated only with computer-based simulations using the estimated optimal frame length. The results show that average number of frames, i.e., the average delay, increases exponentially with the number of tags.

Assuming that the number of tags cannot be known a priori, the algorithms proposed in [15,16] estimate the number of tags contending in a frame in order to select the optimal frame length to be used in subsequent frames.

While the works described before use a constant number of tags contending in all the frames, the work in [17] considers that the already identified tags withdraw from contention in the following frames. The authors in [17] have estimated the average number of frames required to identify a full set of tags using different frame lengths. The results show that with a given frame length, the number of frames to solve the contention increases exponentially with the number of tags. However, they do not determine if there exists an optimal frame length that may minimize the delay of the discovery process.

In terms of energy consumption, the works in [18,19] compare the energy consumed by the tags and the reader using several variants of FS-ALOHA. The results show that, as in the case of the average delay, using a fixed frame length the energy consumption in FS-ALOHA grows