Computer Networks 59 (2014) 171–183

Contents lists available at ScienceDirect

Computer Networks

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

Automatic meter reading in the smart grid using contention based random access over the free cellular spectrum

Elias Yaacoub *, Adnan Abu-Dayya

Qatar Mobility Innovations Center (QMIC), Doha, Qatar

ARTICLE INFO

Article history:
Received 2 June 2013
Received in revised form 12 September 2013
Accepted 30 October 2013
Available online 7 November 2013

Keywords:
Automatic meter reading
Advanced metering infrastructure
OFDMA
Aloha
Random access protocols

ABSTRACT

Real-time transmission of smart meter measurement data is investigated. A contention based approach exploiting the unused cellular spectrum, e.g. of 4G Long Term Evolution (LTE), is proposed. The proposed approach uses subsets of LTE resource blocks (RBs) as allocation units. It is based on channel aware reservation slotted Aloha over orthogonal frequency division multiple access (OFDMA) using time/frequency slots, which leads to a reduction of collision probability, prevents collisions in the transmission phase, and allows detecting these collisions at the reservation phase.

The proposed method relies on an access point (AP) that indicates the "available" OFDMA subcarriers to the contending devices after receiving this information through coordination with the cellular base station (BS): The BS informs the AP of the LTE RBs that it intends to keep free for a certain time period (e.g., because the current load on the network does not mandate their allocation to primary cellular users). Then, with the proposed approach, the AP transmits pilot signals on the free channels so that they can be used by the contending devices.

Simulation results show that a large number of smart meters can be successfully accommodated within a limited coverage area with the proposed approach, while transmitting their measurement data in real-time.

1. Introduction

The increasing power consumption is putting additional pressure on the current power grid that is pushed to the limit and thus is becoming unsustainable. This motivates the ongoing activities and research related to developing a "Smart Grid" [1].

The main purposes of the smart grid are: adding intelligence to the grid in order to perform self-coordination, self-awareness, self-healing, and self-reconfiguration, boosting the deployment of renewable energy sources, augmenting the efficiency of power generation, transmission, and usage, in addition to shifting and customizing consumers' energy demands by managing peak loads via demand response (DR) techniques. This necessitates advanced distribution automation and dynamic pricing models relying on automatic meter reading (AMR) and advanced metering infrastructure (AMI) [2].

The AMI is based on systems that measure, collect, and analyze energy usage and interact with smart meters through some communication media [3]. The benefits of smart meters include reducing peak demand via demand response programs, better planning of the electricity network and optimized generation/maintenance, in addition to energy savings due to real-time information feedback and more frequent and accurate billing [4].

AMI communications consist mainly of two networks [5]:

* Corresponding author. Tel.: +974 44592736.
E-mail addresses: eliasy@qmic.com (E. Yaacoub), adnan@qmic.com (A. Abu-Dayya).

1389-1286/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.bjp.2013.10.009

– A home area network (HAN) where power consuming devices inside the home communicate with the power supplier, generally through a gateway integrated into the smart power meter. This communication can take place via low power wireless transceivers or in home power line communications (PLC).
– A neighborhood area network (NAN) connecting energy meters to data aggregators/collectors. This link can be established wirelessly, by a data wireline connection to the smart meter, or over the power lines via PLC technology. The aggregation stations then communicate with the power utility's central servers using leased access lines, wireless microwave links, or PLC.

This paper presents an AMR/AMI communication approach that can be applied either to directly transmit the data from the smart meters to the utility servers, or to transmit data collected by aggregators to these servers. It allows to dynamically benefit from the unused cellular spectrum that will be free for a given time period. Meters/aggregators then contend for the spectrum using a random access Aloha-like contention based approach. The proposed approach implements random access on time–frequency slots in an orthogonal frequency division multiple access (OFDMA) system, using the channel state information (CSI) to optimize the time–frequency slot reservations and perform efficient transmissions while minimizing collisions.

The paper is organized as follows. An overview of related work is presented in Section 2. Section 3 describes the AMI communication approach using the free cellular spectrum. In Section 4, the details of the random access contention based scheme, which constitutes the core of the proposed AMI approach, are presented. Simulation results are displayed and assessed in Section 5. Finally, Section 6 concludes the paper.

2. Related work

This section overviews the most relevant works in the literature, and outlines the differences with the proposed approach.

In [6], PLC is suggested for communications between smart meters and a concentrator that relays the data using GPRS to a central information system. However, PLC faces the challenge of the lack of capacity at higher frequencies [4]. Furthermore, measurements have shown that the characteristics of the PLC channel vary significantly between different countries or regions, due to different wiring practices and loads connected to the system [1]. Hence, a solution suitable for one country might not be suitable for another. OFDMA was proposed in [1] to enhance the throughput and reliability of PLC. Although significant enhancements were reached, it was noted in [1] that more sophisticated channel estimation and adaptive feedback techniques are needed in order to further enhance throughput and reliability.

Wireless communications are seen in many cases as the most inexpensive path to the deployment of smart meters, compared to laying additional cables or upgrading power distribution hardware to accommodate PLC data communications [5]. Thus, another approach consists of forming a mesh network from thousands of meters using protocols in the public industrial scientific and medical (ISM) frequency bands. The mesh network is used to route the data to an aggregator that relays data between the meters and the utility, generally using cellular data services such as GPRS [3]. However, with mesh networks, problems related to security and signal privacy need to be overcome in order to promote its adoption for AMI [4].

In [3], the use of TV white spaces is suggested for AMI communication in a two-tier approach: The proposed approach consists of using WhiteFi, a system providing connectivity similar to Wi-Fi using the white spaces [7], in order to collect the data of smart meters by aggregators. Then, these aggregators relay the collected data to the utility provider using IEEE 802.22.

It can be seen that most of the previous work investigates the NAN wireless communication part. In fact, within the HAN, devices could connect to the smart meter using established protocols such as Bluetooth, ZigBee, and WiFi. The main challenges remain for NAN communications.

In [8], a queuing-based resource allocation framework for OFDMA-based wireless networks was proposed. The model can be useful as the last-mile or high speed backhaul part of the power grid communications infrastructure.

In [9], WiMAX communications are used to transmit the data of phasor measurement units (PMUs) in the smart grid. The unsolicited grant service (UGS), real-time polling service (rtPS) and best-effort (BE) WiMAX scheduling services are compared and analyzed. PMU measurements are strictly delay-sensitive and they can trigger protection and control systems. The results of [9] show that UGS performs best while consuming a significant amount of radio resources. Although periodic frequent AMR readings are important in the smart grid, they can be performed at intervals of few minutes, and are not as critical as critical messages from PMUs that could be due to an alarming situation in the grid.

The performance of a heterogeneous (HetNet) WiFi/WiMAX network was shown to lead to a better delay performance in transmitting the meter readings than a pure WiMAX network in [10]. In fact, it is expected that this two-tier network, with the presence of WiFi access points closer to the smart meters, and ready to relay the aggregated meter data (using significantly less wireless channels) to the WiMAX network, would lead to better results. However, it should be noted that the proposed approach can be implemented in a HetNet framework, either by implementing the method itself on the two hops (between the meters and aggregator, then between the aggregators and BS), or on the first hop (between the meters and aggregator, then using LTE between the aggregators and BS), or on the last hop (using WiFi between the meters and neighboring aggregators, then using the proposed approach between the aggregators and the BS).

With AMI, most of the traffic is expected to be in the uplink direction. Hence, LTE Time Division Duplex (TDD) was investigated in [11] as a possible solution for AMR/AMI using LTE TDD configurations 0, 1, or 6, that are uplink biased. In [12], it was compared with LTE Frequency