Energy efficiency challenges in home capillary M2M networks

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***Abstract*—Energy efficiency is an important metric when it comes to battery operated or self sustained nodes for M2M communications. The success of a M2M network is connected to the lifetime of the nodes within the network, where a reduction of energy consumption can prolong the lifetime of such networks. This paper discuss the energy efficiency of a M2M network by researching implementations of CSMA/CA, sleep/wake-up management and energy harvesting. Here a brief explanation of the techniques, some issues they introduce to the network and how these could be useful in order to improve the energy efficiency of M2M networks is provided. It was shown that effectively using CSMA/CA protocols and combining it with scheduling to both reduce collision and idle listening introduce improvements of efficiently utilizing battery energy. With the addition of energy harvesters this can prolong the lifetime of batteries or make nodes self-sustainable, however some energy sources need more research in order to be concluded as useful.**

***Index Terms*—Machine-to-machine communications, energy efficiency, CSMA/CA, sleep/wake-up, energy harvesting**

I. Introduction

Information and communications technology, also known as ICT, play a large role in the society of today. Not only is it heavily integrated but it is also constantly evolving, for instance the now upcoming 5G technology. ICT is a broad umbrella term and one area within is the wireless communications, which contain serveral technologies that are used daily by the population mostly through a wide variety of different devices. Another evolving concept within ICT is what is known as the Internet of Things or IoT where newly produced devices have the potential to be connected to a communications system. This in turn is related to a specific type of communications area called Machine-to-Machine (M2M) communications. As the name implies, M2M communications is systems where devices are connected to each other and can transfer information between them without or with minimal human intervention. M2M communication has multiple applications to society in areas such as industry, health and safety, homes, transportation, etc.

To narrow the topic down, this report aims to look at different issues and potential solutions regarding energy efficiency mentioned by relevant literature and studies, of M2M communications system within the homes of citizens. The M2M communication within a household setting typically consists of terminals in wireless local area network (WLAN) that operate on battery power, and they are expected to operate unattended over extended periods of time [1]. The replacement of batteries for a large number of inexpensive devices is not economically preferable and it also defies the purpose of automation of data transmission. This leads to the requirement of a low-energy consumption scheme.

The focus of the report also lie upon the capillary M2M communication, which is a sub part of the communication architecture for home M2M networks (see Figure 1) described by Chen et al. [1]. Within a WLAN, The connections between terminal to terminal, and between terminal to gateway could adopt different radio technology, such as WiFi, Bluetooth, etc. A proper management of access control and quality of service (QoS) would make an impact on energy efficiency. Since the connection range for these technologies are confined to local area network, the cellular M2M communication will not be of major interest in this report.

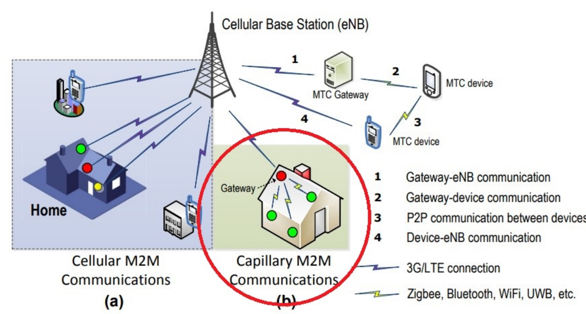

Fig. 1. The home M2M networks architecture. The circled part indicates the scope of this report. Adapted from [1]

II. Background

This section will explain the basic principles of the three following concepts: carrier sense multiple access with collision avoidance (CSMA/CA) protocol, sleep/wake-up management and energy harvesting. These are three concepts among several in which the energy efficiency of a M2M system may be analyzed.

A. CSMA/CA

CSMA/CA is a medium access control (MAC) protocol, which is adopted by several 802.11 (WiFi) and 802.15.4 (Zigbee) standards, where the main idea of the protocol is enforcing the stations to sense the channel before transmitting. If the channel is sensed busy, then the station will refrain for a given back-off, in order to avoid collisions with other nodes. Note that the 802.11 MAC does not include collision detection (CD) scheme as in 802.3 Ethernet, since the ability of detection requires receiving signal at the same time as transmitting, which is more costly to implement on a wireless hardware. Additionally, the WiFi adapter may not be able to detect all collisions, due to fading and a problem known as hidden terminal [2].

For a contention-based random access protocol such as CSMA/CA, the re-transmissions after a collision are major contributors of power consumption during channel access [1]. In a large scale network with a large number of M2M devices, a better coordination scheme is needed to overcome congestion, in order to improve the energy efficiency of the network.

B. Sleep/wake-up management

The sleep mode aims to reduce the idle listening of the device. During idle listening, the radio transceiver is switched on, and the power consumption continues. Since it is quite often that M2M devices collect and transfer data in a periodic manner, the duty cycle can be manipulated to improve energy efficiency. There is a trade-off between the amount of energy saved and the service availability of the device when reducing the time the device is idle and listening to the channel.

802.11 has defined a power saving mode (PSM), such that devices will listen to the delivery traffic indication message (DTIM) at beacon interval from the access point (AP). If there is no incoming data, the device would be put into sleep mode and only wake up at the next DTIM interval. However this static triggering mechanism is bound to AP beacon interval. Some packets may be buffered at the AP, meaning the delivery would be delayed [3]. Therefore a more dynamic management of sleep schedule is often needed.

C. Energy harvesting

Another method to improve energy efficiency is by utilizing energy harvesting. The idea of energy harvesting, also known as energy scavenging, is to convert energy from the surroundings to electric energy that can prolong the lifetime of the devices. The surrounding sources of energy harvesting can be categorized in two main groups: natural sources such as solar and wind energy, and artificial sources such as human motion and vibrations from operating machines [4]. In the home M2M systems perspective, the most probable sources that energy can be harvested from are solar energy, RF energy and kinetic energy from motion artefacts. This, since not only are they more convenient to harvest within the home but also because much research is dedicated toward these topics. The utilization of energy harvesting for M2M devices introduces a possible reduction of both needed service and costs. However, according to D. W. K. Ng and R. Schober [5], this also introduces new challenges in designing the network. Due to how the surrounding energy can vary with time, new designs for transmission scheduling and power allocation needs to be implemented to compensate for this where battery storage capacity and system data rate requirements of the devices must be taken into consideration. Another challenge when using energy harvesting was found that when the harvesters provide exceedingly large amounts of energy the transmitter of the device must discharge the batteries to protect the batteries from overflowing, which would decrease the efficiency of the system [5].

III. Potential Solutions

In this section, several more recent techniques and optimizations proposed by researchers are presented. These solutions are regarded as enhancements of the existing topics mentioned in Section 2. The overview of their methods will be described.

A. Adaptive tuning of CSMA/CA

Di Francesco et al. [6] proposed an adaptive access parameters tuning (ADAPT) algorithm, in which it analyzed the following three parameters in CSMA/CA.

(i) the minimum backoff exponent
(ii) the maximum number of backoffs
(iii) the maximum number of retransmissions

Based on observations, The reliability (the ratio of success delivery) increases monotonically when parameters (i)-(iii) increase. It remains true up to a certain threshold, then the increase of reliability becomes less significant. Additionally, the value (i) increases reliability with lower power consumption than that of the value (ii).

The ADAPT algorithm exploits the above observations trying to minimize the trade off between reliability and energy conservation. It dynamically adjusts the three parameters to achieve this. Furthermore, [7] introduced a heuristic way to estimate reliability without ACK message, so called blind adaptive tuning algorithm (BADAPT). The approach uses locally measured busy channel probabilities to predict reliability. Under single-hop network, the result shows there is 14.8%–15.5% reduction on energy consumption while maintain the same reliability as ADAPT.

B. Hybrid MAC protocol with scheduling

In high density networks, CSMA/CA scheme suffers greatly from collisions, hence downgrading the overall performance of the network substantially, especially when taking the power consumption used for re-transmission into consideration. Some researches has been done to solve this by combining CSMA/CA with time division multiple access (TDMA), to create a hybrid MAC protocol [8], [9]. These approaches reserve time slots in a high contention state to ensure the success of transmission, in attempt to mitigate the collision. To take this one step further, Al-Janabi et al. [6] proposed the addition of a sleep/wakeup mode schedule called HSW-802.15.4, such that nodes which are not participating in contention will be stay in sleep mode for a longer time in order to conserve energy.

The main idea is to divide all nodes into subgroups (SG). The coordinator will send out a scheduling message, known as the ST, which contain information about the sleep/wake-up times for each SG. In each TDMA slot only the nodes in the selected SG will be able to compete using CSMA/CA. The rest of nodes in other SG are forced to enter sleep mode according to their ST message. The sleep mode cycles are also dynamically computed based on the certain SG experience of failure and the amount of back-off periods a TDMA channel has.

Simulations have shown that the proposed HSW-802.15.4 protocol can efficiently utilize the energy of the battery by 40%–60% depending on the number of groups. It demonstrates a better channel utilization than IEEE 802.15.4 in high density networks. However, while small in density, HSW-802.15.4 costs some extra energy due to the header load of ST message.

C. Enhanced CSMA/CA with energy transfer

Zhao et al. [10] proposed an integration of RF signal-based wireless energy transfer (WET) into classic CSMA/CA, that allowed stations (STAs) to harvest energy from the access point's (AP) downlink data transmission. Two enhancements of this scheme were later proposed in [11], namely energy-back-off-interval aided CSMA/CA (EBI-CSMA/CA) and energy-packet aided CSMA/CA (EP-CSMA/CA).

In EBI-CSMA/CA, STAs send an energy request pulse to the AP when the channel is free, then the AP broadcasts all STAs to initiate energy transfer, within a back-off interval that is longer than the more conventional back-off intervals. In EP-CSMA/CA, such request/reply pulses during back-off intervals are omitted in order to avoid frequent transmissions that result in a higher power consumption. Instead, the AP initiates the dedicated energy transfer by generating a energy pack. The transfer duration is approximately the same as for a normal packet. A longer energy transfer time in EP-CSMA/CA than back-off interval suggests that STAs do not have to detect energy level and send requests as frequent as in EBI-CSMA/CA. According to this, EP-CSMA/CA is more energy efficient than EBI-CSMA/CA. However, there is a drawback as the EP-CSMA/CA protocol may experience more back-off intervals than its EBI-CSMA/CA counterpart. The reason being that STAs in EP-CSMA/CA have to complete the conventional back-off processes without any additional operations before sending a request for the dedicated energy transfer. In consequence, this, together with the fact that the DIFS time slot has to be inserted after each energy transfer, imply that EP-CSMA/CA has a lower up-link throughput.

D. Motion energy harvesting

In a study by M. Gorlatova et al. different human motions were evaluated, such as walking, running, cycling and walking upstairs/downstairs [12]. Within a household setting the walking and walking upstairs/downstairs motions are of most interest. In this study it was found that regular walking could provide powers in the range of $150 - 200\ \mu W$. The cases of walking upstairs and downstairs concluded that harvesters can pick up more energy from walking downstairs than regular walking, however walking upstairs proved to be worse. Through the use of smart-textiles, which utilize piezoelectric materials [13], this motion energy can be harvested by the people living inside the home e.g by using shoe soles of this type of textile. Another example of products utilizing motion energy is environmental-vibration based power generation by Fuji Electric which instead of using piezoelectric material they use magnetostrictive material to enable energy harvesting for sensors that might not be able to directly be attached to humans [14].

E. RF energy harvesting

There are vast amounts of devices, especially in urban environments, emitting radio frequency such as mobile phones, routers and radio base stations. This RF energy is sent out as a means of transmitting information and is often transmitted omni-directional. These signals can then be picked up by devices that are not the intended target of the information and instead of receiving the information within, the RF signal is converted to electric power through the use of a rectifier circuit or rectenna circuit. In a study by R. K. Sidhu, J. Singh Ubhi and A. Aggarwa [15], it is mentioned that a harvesting model may be designed according to the environment it is intended to be used in since different devices uses different spectrums. An indoors environment such as a home could utilize the RF emitted from Wi-Fi APs and mobile devices which use a fixed spectrum and would therefore not need to use the whole spectrum to receive from. M. A. Andersson et. al. discuss the feasibility of using graphene antennas for RF energy harvesting [16], which may be applicable to surfaces such as paper, textiles and plastics. Through EM simulations with state-of-the-art sheet resistances for graphene rectennas, an antenna used as rectifier, to convert RF-to-DC energy it was shown that the graphene antennae could harvest energies ranging between $1 - 50\ \mu W$. This show that a RF energy harvesting graphene rectenna has quite little use as it is now, but could potentially prove to be efficient under more favourable conditions or in the future if the ambient RF energy available increase or if more ultra-low-power technologies are developed.

IV. Conclusions

In this paper, the techniques of CSMA/CA, sleep mode, and energy harvesting are discussed as the common approaches to improve energy efficiency of capillary M2M networks. Several related works have been summarized in this paper, in which they suggest the combination of the above techniques could further conserve more power. In the following, the key methods that have shown their effectiveness in energy efficiency enhancement are highlighted.

- Dedicated energy packet in CSMA/CA protocol to prolong energy transfer duration.
- Adaptive tuning of backoff interval in CSMA/CA to maintain reliability while conserve power.
- Hybrid protocol of CSMA/CA with TDMA to reduce chance of collisions due to contentions in high density networks.
- Introduce new products that enable harvesting of motion energy in daily household activities.

As the RF energy harvesting through the use of graphene rectennas was shown to provide minimal power in the conditions during the analyzed study, this could be an interesting area for future research to see whether it can be useful in other settings as graphene is a much beneficial material due to the abundance of carbon. The problem concerning battery discharges in order to protect them from overflowing, and improving battery lifetime in general is a topic for future research that could provide increased efficiency as well.

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