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BACnet–EnOcean Smart Grid Gateway and its application to demand response in buildings

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ABSTRACT

Demand response (DR) systems are the key component of the Smart Grid, which balances electricity generation by temporarily reducing or increasing demand-side consumption based on the real-time state of a power grid. In this study, we developed an infrastructure of BACnet–EnOcean based DR system for buildings. We describe an interface between two well-known international communication standards: BACnet and EnOcean. The BACnet–EnOcean Smart Grid Gateway (BE-GW) implements this interface, and we develop the EnOcean Load Control and Metering Device (ELCMD) to measure energy metering of each building appliance and control the load using wireless communications. Additionally, we develop an experimental facility to demonstrate how the BE-GW and ELCMD can be implemented in buildings for DR applications. Experimental results show that electricity consumption in the experimental facility can respond to real-time changes in the electricity price. We also measure the average communications delay of the energy metering service and load control service, and verify that the DR implementation satisfies the time-critical requirements of real-time DR services in buildings.

1. Introduction

Smart Grid (SG) is an electricity delivery system designed to efficiently transport, convert, and distribute power from producers to consumers, and which integrates with communication and information technology. The main purpose of SG is to help balance power generation and consumption. One of the current frontiers capitalizing in SG technologies is demand response (DR), in which power system operators achieve system-wide demand reductions by providing financial incentives for users to change their electricity consumption patterns. These shifts in energy use and load reductions, or 'sheds', can reduce peak demand and help lower the risk of potential disturbances, avoid additional capital cost requirements for additional plants, and transmission and distribution infrastructure, as well as avoid the need for more expensive and less efficient operating plants [1].

Today, the majority of electricity demand comes from buildings and industry. According to the U.S. Department of Energy, buildings (residential and commercial) accounted for 74% of the total electricity consumption in the U.S. in 2010. By the year 2035, this percentage is expected to increase to 77% [2]. Therefore, a well-designed and well-utilized building DR system could lead to great system-wide benefits in terms of improving power system and economic efficiency.

In recent years, there have been many reports of DR algorithms and strategies for buildings end users. The authors of these studies typically indicated that their DR algorithms should be implemented using fully automated equipment, which can efficiently manage and meter the load of decentralized building appliances [3–6]. However, there have been relatively few studies discussing how to implement DR systems in buildings [7–9,11]. In 2007, the Olympic Peninsula Project demonstrated a successful building DR system using an existing BACnet-based building automation system (BAS) [7]. But due to expensive cabling, and complex installation and maintenance, significant market penetration has not been achieved. Wireless sensor networks (WSN) have significant advantages in terms of cost and flexibility of installation and maintenance, and represent a promising approach to realizing home and buildings DR systems.

All existing approaches to creating wireless DR systems are based on ZigBee [8–11]. In 2008, Handa et al. proposed integrating ZigBee WSN into KNIVES, a wired system that allows for demand control [8]. However, their ZigBee devices did not have load control or energy metering functionality; they simply developed ZigBee devices to monitor the temperature for the KNIVES system. In 2012, Kuzlu et al. reported a ZigBee-based hardware implementation of a home energy management system for DR applications [9];

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Nomenclature

SG	Smart Grid
DR	demand response
BACS	building automation and control systems
HVAC	heating, ventilation, and air conditioning
RTP	real-time electricity pricing
WSNs	wireless sensor networks
BACnet	building automation and control network
BE-GW	BACnet–EnOcean Building Smart Grid Gateway
ELCMD	EnOcean load control and metering device
MS/TP	master–slave/token-passing
WAN	wide-area-network
LCO	load control object
AO	accumulator object
EEP	EnOcean equipment profiles
ID	identification
ACK	acknowledgment

however, they considered only a very small home system. Further study is warranted to implement a WSN-based DR system for larger buildings. The main challenges are that, in large commercial buildings (more than 100,000 ft^2), the time delay of a WSN-based system will increase rapidly with the communications distance. The reason for this is that a WSN-based system requires wireless repeaters to relay messages (the indoor signal range of ZigBee is 30 m). In 2013, a BACnet–ZigBee-based buildings energy management system was reported, which considered a daylight-responsive control and the presence of people to reduce the energy consumption in buildings [10]; however, this system did not have DR functionality. Very recently, Hong et al. reported a BACnet–ZigBee based DR system, which can be applied to larger buildings [11]; however, most ZigBee devices use batteries for the energy supply, so thousands of batteries would need replacing every year in modern buildings, which has environmental and maintenance cost issues. For this reason, energy-harvesting WSNs may be a better choice for communication systems in buildings. In 2012, EnOcean became the first international wireless standard to be optimized for energy-harvesting WSNs in buildings [12]. EnOcean has three main benefits: it uses a wireless short-packet protocol that achieves ultra-low power consumption; it can harvest energy from its environment (and remain battery-free, thereby reducing maintenance costs); and it is primarily designed for building automation systems [13].

Recently, some companies have developed energy-harvesting sensor devices based on ZigBee. However, it should be noted that ZigBee is a relatively heavy protocol stack because ZigBee is designed for many general-purpose applications, and this will result in relatively high energy consumption. However, the EnOcean protocol is simpler, as it is designed only for building automation and provides an ultra-low-power wireless communications standard, which can be powered by energy harvesting devices. For this reason, EnOcean may be a better choice for DR application in buildings. However, in some large systems, such as high-rise buildings, EnOcean requires a large bandwidth backbone. To address this issue, we use BACnet as a backbone, which is an international building automation standard and contains specifications for DR applications [14].

In this study, we developed a BACnet–EnOcean Building Smart Grid Gateway (BE-GW) that maps the DR application of BACnet to that of EnOcean, and vice versa, to combine the flexibility of the EnOcean networks with the large bandwidth wired BACnet backbone. Additionally, we developed the EnOcean load control and metering device (ELCMD) and constructed an experimental facility to demonstrate how the BE-GW can be implemented for DR applications in buildings. We also measured the communication delay to verify that the BE-GW developed here satisfies the time-critical requirements of real-time DR service in buildings.

The remainder of this paper is organized as follows. Section 2 presents the integrated BACnet and EnOcean DR systems. Section 3 describes the SG strategy within BACnet and EnOcean protocols. Section 4 details the architecture of the BE-GW. Section 5 introduces DR translation methods in BE-GW. Section 6 discusses implementation of BE-GW and ELCMD. Section 7 presents a practical analysis using an experimental facility. And lastly, in Section 8, major findings are summarized and future work suggested.

2. Integrated BACnet and EnOcean DR system

BACnet provides six options for its data link layer protocol: BACnet/IP, Ethernet, master–slave/token-passing (MS/TP), ARCNET, point-to-point (PTP), and LonTalk. Currently, BACnet/IP is often used as the backbone for BACS [15–17], because an IP network is the quickest way to gain access to the Internet, which is a world-wide wide-area-network (WAN). BACnet MS/TP is widely used as subnet in BACnet because of its cost-effectiveness and ease of implementation [16–19]. The BACnet MS/TP protocol was designed for implementation on a single-chip microprocessor. It uses a twisted-pair cable and provides a maximum communication distance of 1200 m.

Fig. 1 illustrates the proposed integrated BACnet and EnOcean DR system in buildings. The overall system is composed of:

- Building DR server
- BACnet routers
- BE-GWs
- ELCMDs
- Building appliances

As shown in Fig. 1, the utility company generates an RTP signal, which is transmitted to the building DR server via the WAN. According to this RTP signal, the building DR server responses to dynamic changes in electricity prices: it decreases electricity consumption at high-price hours, or shifts from high-price hours to low-price hours. This not only helps reduce peak demand, which helps avoid grid instability, but also helps consumers reduce their total electricity bill. The building DR server sends out the load control signal; this is transmitted through the BACnet/IP backbone, BACnet router, BACnet MS/TP network, BE-GW, and ELCMD, and eventually arrives at each building appliance, such as air conditioners, lights, water heaters, energy storage system, and electric vehicles. Each building appliance is connected to one ELCMD. The ELCMD has three functions: load control, energy metering, and wireless communication (EnOcean standard). It reports the energy metering information of each building appliance to the BE-GW and eventually to the building DR server. The total building energy usage data is transmitted to the utility company through the WAN. Thus, the building's energy consumption remains transparent for the supplier and customers.

3. Smart Grid strategies in BACnet and EnOcean protocols

The BACnet protocol and EnOcean protocol both have their own DR applications. In this section, we explain the SG strategies used in BACnet and EnOcean.

3.1. SG strategies used in BACnet

The Smart Grid Working Group (SG-WG) for BACnet was established recently to address issues related to communication between BACS and utility providers, with a new focus on SG