Synchronised Power Scheduling of Widely Distributed Refrigerators using IoT

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Abstract: The paper proposes an IoT controlled platform to remotely monitor and control appliances in the residential sector. An IP-based synchronized wireless mesh network is implemented through IoT hardware (based on a NodeMCU) and Google Sheets to monitor and schedule the operation of aggregated domestic refrigerators under a Model Predictive Control (MPC) scheme. Benefits afforded by the proposed technique are investigated through experimental trials from VonShef 13/291 (50W), iGENIX IG 3920 (55W) and Russell Hobbs RHCLRF17B (50W) domestic refrigerators sited in three different domestic locations in the city of Lincoln, UK. Results demonstrate the ability to monitor and control widely distributed networks of refrigerators and adaptively schedule the appliances to reduce peak operational loads and facilitate Demand Side Response (DSR). Further widespread expansion of the proposed technique would allow for a rapidly deployed regional DSR strategy to aid grid stability. Ultimately the underlying principles also could be used for the co-ordinated scheduling of other distributed appliances and equipment, both domestic and industrial.

1 INTRODUCTION

The emergence of IoT and Thermostatically Controlled Loads (TCLs) can be utilized to facilitate the implementation of ancillary services and demand-side response schemes in power systems. A key factor for improving the management of energy consumption in the residential sector is by the remote real-time supervision and control of domestic appliances. Consequently, the need for remote aggregated scheduling of widely distributed networks of domestic appliances is gaining increasing attention for smart cities (Talari et al. 2017).

Recently published research shows the potential of accessing home appliances remotely and implementing intelligent smart home systems based on web-based and smartphone applications (Pavithra and Balakrishnan 2015, Vishwakarma et al. 2019, Li et al. 2019, Mandula et al. 2015, Govindraj et al. 2017, Lokhande and Mohsin 2017, Al-Ali et al. 2017 and Xiao et al. 2018). Vishwakarma et al. 2019 propose the implementation of IoT connections for home appliances through Google Assistant (voice commands) as well as World Wide Web services to switch on/off devices such as fans and lighting etc. without requiring any physical interaction, for the elderly or those with disabilities for instance, whilst Mandula et al. 2015 proposes an IoT based home automation system using an Arduino microcontroller for indoor and outdoor remote control of appliances. It develops an Android-based application to provide on/off control of six home electrical appliances namely lamp, AC, fan, refrigerator, TV and washing machine. Furthermore Li et al. 2019 uses a STM32F407 embedded development board for remote environmental monitoring. It shows how the integration of the STM32F407, Reduced Media Independent Interface (RMII), Flexible Static Memory Controller (FSMC) interface and web development can provide a real-time remote monitor function. Govindraj et al. 2017 develops an Android-based application for a smart home automation system using ThingSpeak for data acquisition and visualisation, whilst Al-Ali et al. 2017 propose the inclusion of Big Data in IoT with a unique IP address in a mesh wireless network of devices and recommend users to remotely monitor and control devices and generate on-line bills via a mobile app. Xiao et al. 2018 employ an ESP8266 and a MCU STM32F103 microcontroller to realise a home appliance control system with a mobile terminal for remote control, whilst Hanumanthaiah et al. 2019

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develop a low-cost smart switch system based on an Arduino UNO interface to facilitate remote controllability and cloud analytics. Finally, home automation using Message Queuing Telemetry Transport (MQTT) and Raspberry Pi is proposed by (Upadhyay et al. 2016) to enable measurements of temperature and humidity. Such systems enable users to benefit from the remote monitoring and control of devices at isolated sites. However, more substantial benefits can be obtained from the coordinated control of widely distributed home appliances for aggregated load management and load shed for Demand Side Response (DSR) purposes. A suitably widespread mesh network affords the opportunity to schedule and monitor the operation of distributed domestic appliances simultaneously to collectively improve energy efficiency and reduce peak power consumption on the electrical grid. Here then, the paper proposes the implementation of a Model Predictive Control (MPC) scheme, initially proposed by Zavvar Sabegh and Bingham 2019, to provide the co-ordinated scheduling of power to domestic refrigerators of a number of households around the City of Lincoln, UK. Measurements are taken from the refrigerators under the IP-based wireless mesh network and Google Sheets is used for cloud data acquisition and monitoring. The remaining sections of the paper are organised as follows: Section 2, a synchronized wireless mesh network is proposed to remotely monitor, and schedule domestic refrigerators; Section 3 describes the experimental setup to implement the proposed network on three widely distributed refrigerators using a microcontroller and Google Sheets. Section 4 presents the result of the experiments for monitoring and scheduling modes. Section 5 concludes the work presented in the paper.

2 IP-BASED SYNCHRONIZED WIRELESS MESH NETWORK

The proposed network shown in Figure 1 consists of two main parts: the server and client units. Client units are widely deployed at different sites. Each client is assigned a unique public IP address to provide remote access and are used to collect measurements (e.g. internal fridge temperature, ambient temperature and the power consumption of the fridge), send the measurements to the server via received HTTP requests, receive control instructions from the server and apply them to the house appliances (e.g. fridge on/off commands). The server can be located anywhere with Wi-Fi access and is used to send control commands and HTTP requests to the clients using the 'port forwarding' feature of the routers to collect sensor data simultaneously (the centralized coordinator among the clients) and send them to the Google Sheets for data acquisition and monitoring—see Figure 1.

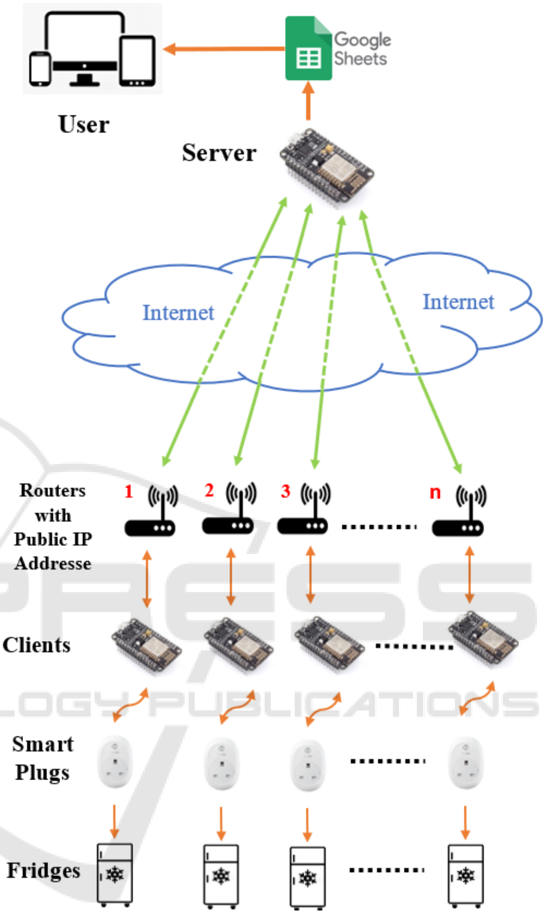
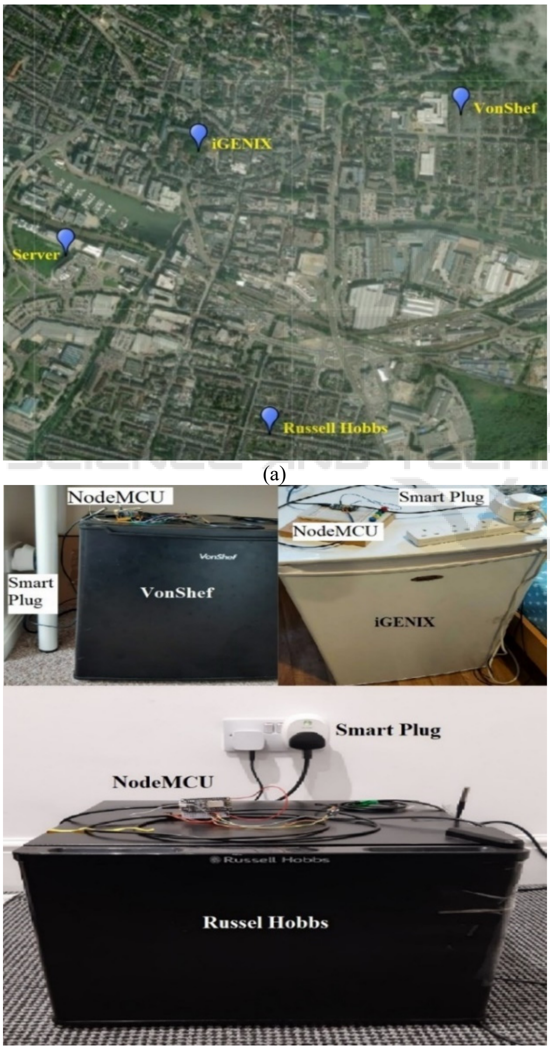


Figure 1: IP-based synchronized wireless mesh network structure.

3 DEPLOYMENT AND EXPERIMENTAL SETUP

The study uses a wireless IoT scheme based on a synchronized wireless mesh network to remotely monitor and schedule three domestic refrigerators under Binary Quadratic MPC control to facilitate DSR load-shedding events. The location of the fridges is shown in Figure 2. The server microcontroller is sited at the University of Lincoln, UK. The test facility components and hardware setup are given in Figure 2. Trials are conducted using a

VonShef 13/291 (50W), iGENIX IG 3920 (55W) and Russell Hobbs RHCLRF17B (50W) domestic refrigerators. It is important to note that the RHCLRF17B uses thermoelectric cooling technology, so no compressor is employed. Each refrigerator is instrumented with two DS18B20 waterproof sensors to measure the internal and ambient temperatures, a NodeMCU microcontroller to implement the Binary Quadratic MPC algorithm and a TP-Link Smart Wi-Fi Plug (HS110) to provide on-off control and measure the real-time power consumption of the refrigerators. Moreover, another NodeMCU is located at the University of Lincoln as a server to request the data from clients simultaneously and send them to Google Sheets.



(a)

(b)

Figure 2: System setup (a) The location of the refrigerators in the City of Lincoln, UK (b) hardware are fridges for measurement and control.

4 RESULTS

Measurements are taken with a fixed sampling period of 60 seconds to show the performance of the IP-based synchronized wireless mesh network under conditions of i) the refrigerators operate in isolation without any scheduling controller to show the monitoring feature of the proposed network, and ii) the custom Binary Quadratic MPC algorithm is implemented for jointly scheduling the operation of refrigerators in DSR events.

4.1 Trial A: Refrigerators Operate in Normal Operating Conditions without a Scheduling Controller (Monitoring Mode)

An initial experiment is conducted under normal operating conditions with no co-ordinated MPC scheduling applied. This effectively shows how the proposed network can monitor the domestic fridges remotely. Figure 3 shows examples of 12-hour experiment trial intervals for each refrigerator's internal temperature, the ambient temperature, individual power consumption and the total aggregated power consumption.

4.2 Trial B: Responding to DSR Events using Power Scheduling

Measurements now show the performance of the synchronized wireless mesh network to investigate how the widely distributed domestic refrigerators can respond to a DSR events using the MPC controller proposed by Zavvar Sabegh and Bingham 2019. The iGENIX, VonShef and Russell Hobbs refrigerators are loaded with 12L, 6L and 3.5L of water, respectively, and the doors remained closed for the duration of the trials. The prediction and control horizon parameters used in the MPC are set to 5 samples. Desired upper and lower temperature setpoints and minimum non-working (minimum OFF) and working (minimum ON) times per cycle for each refrigerator, are shown in Table 1. These are required in order to limit the ON-OFF demand frequency so as to not unduly stress the compressor.

Table 1: Data for iGENIX, VonShef and Russell Hobbs.

Name	Upper Band (ºC)	Lower Band (ºC)	Minimum on time (sec)	Minimum off time (sec)
iGENIX	3	0.5	220	240
VonShef	2.5	0.5	260	200
Russell	8	4	380	100

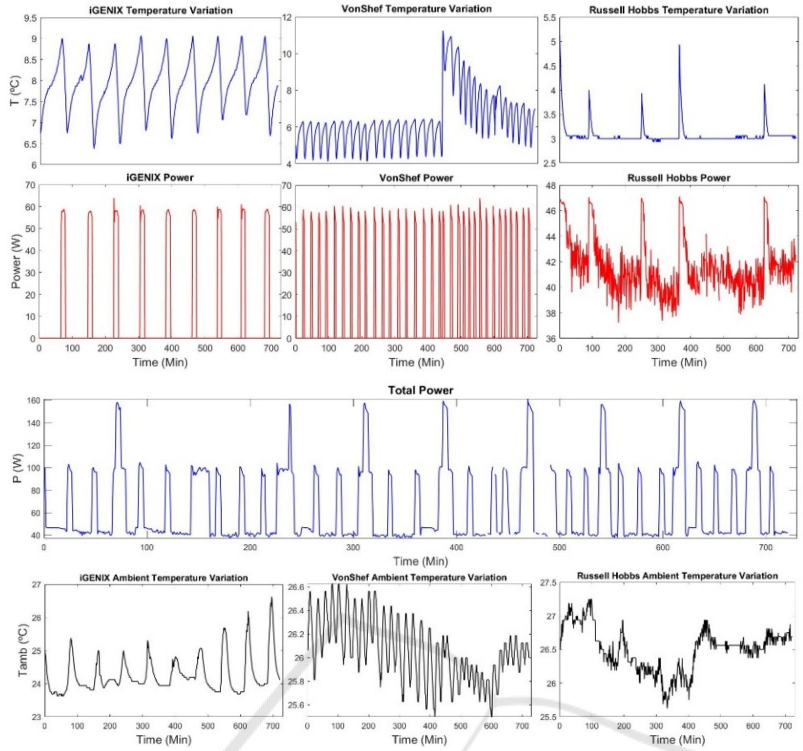


Figure 3: Refrigerators' internal temperatures, ambient temperatures, power consumption and total power for trial A.

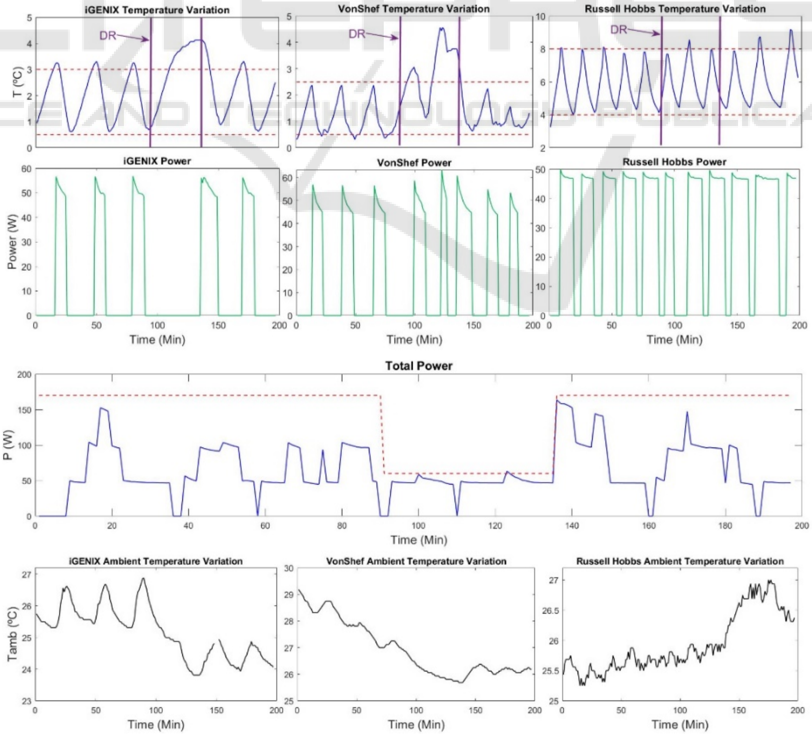


Figure 4: Refrigerators' internal temperatures, ambient temperatures, power consumption and total power for trial B.

Results are given in Figure 4. In this scenario the Russell Hobbs unit is given preferential access to power during the DSR event via the weighting matrices in the MPC controller. DSR demanded with the total power usage of 60W occurs at t = 90 mins and lasts for 45 minutes. As can be seen from the measurements (Figure 4), the refrigerators are able to respond (virtually) instantaneously to power shedding events and the peak power consumption is limited to 60W. Moreover, all the refrigerators maintain their temperatures within required bounds before the DSR event whilst the Russell Hobbs unit remains within temperature limits due to the additional power supply priority attributed to it by the MPC.

5 CONCLUSIONS

In this paper, the IP-based synchronized wireless mesh network is proposed and implemented for monitoring and co-ordinated scheduling of widely distributed domestic refrigerators, and contribute to DSR events using simple 'port forwarding' of domestic routers. The network uses Google Sheets for data acquisition and monitoring in the cloud. The proposed methodology readily lends itself to other house appliances, for instance, heating ventilation and air conditioning (HVAC) systems, or other TCLs.

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