Towards Offering More Useful Data Reliably to Mobile Cloud from Wireless Sensor Network

Chunsheng Zhu, *Student Member, IEEE,* Zhengguo Sheng, *Member, IEEE,*
Victor C. M. Leung, *Fellow, IEEE,* Lei Shu, *Member, IEEE,* and Laurence T. Yang, *Member, IEEE*

Abstract—The integration of ubiquitous wireless sensor network (WSN) and powerful mobile cloud computing (MCC) is a research topic that is attracting growing interest in both academia and industry. In this new paradigm, WSN provides data to the cloud, and mobile users request data from the cloud. To support applications involving WSN-MCC integration, which need to reliably offer data that are more useful to the mobile users from WSN to cloud, this paper first identifies the critical issues that affect the usefulness of sensory data and the reliability of WSN, then proposes a novel WSN-MCC integration scheme named TPSS, which consists of two main parts: 1) TPSDT (Time and Priority based Selective Data Transmission) for WSN gateway to selectively transmit sensory data that are more useful to the cloud, considering the time and priority features of the data requested by the mobile user; 2) PSS (Priority-based Sleep Scheduling) algorithm for WSN to save energy consumption so that it can gather and transmit data in a more reliable way. Analytical and experimental results demonstrate the effectiveness of TPSS in improving usefulness of sensory data and reliability of WSN for WSN-MCC integration.

Index Terms—Wireless sensor networks, mobile cloud computing, integration, usefulness, reliability

1 Introduction

1.1 Integration of WSN and MCC

Wireless sensor network (WSN) is a distributed network, consisting of autonomous sensors that cooperatively monitor the physical or environmental conditions (e.g., sound, temperature, humidity, vibration, etc.) [1] [2] [3]. With the ubiquitous data gathering ability of sensors, WSN has great potential to enable a lot of significant applications in various areas of industry, civilian and military (e.g., industrial process monitoring, forest fire detection, battlefield surveillance, etc.), which could change the way people interact with the physical world. A good example is forest fire detection - by deploying a large number of dispersed sensors into the forest to continuously monitor temperature, humidity and gases, forest fire could be detected in a timely manner and how a fire is likely to spread out could be determined, without the physical observation from personnel on the ground.

Moreover, inherited from cloud computing (CC), which is a new computing paradigm enabling users to elastically utilize a shared pool of cloud resources (e.g., processors, storages, applications, services) in an on-demand fashion, mobile CC (MCC) further transfers the data storage and data processing tasks from the mobile devices to the powerful cloud [4] [5] [6]. Thus, MCC not only alleviates the limitations (e.g., battery, processing power, storage capacity) of mobile devices but also enhances the performance of a lot of traditional mobile services (e.g., mobile learning, mobile gaming, mobile health). For instance, mobile gaming can exploit MCC to move the game engine that requires substantial computing resources (e.g., graphic rendering) from mobile devices to powerful servers in the cloud to greatly reduce the energy consumption of the mobile devices and improve the gaming performance (e.g., refresh rate, image definition, sound effect).

Recently, motivated by the potentials of complementing the ubiquitous data gathering capabilities of WSN with the powerful data storage and data processing abilities of MCC, the integration of WSN and MCC is attracting increasing attention from both academia and industry [7] [8] [9] [10] [11] [12]. Particularly, as illustrated in Fig. 1 about the general scheme (GS) to gather and transmit sensory data for WSN-MCC integration, the sensory data (e.g., weather, traffic, humidity, house monitoring information) collected by various types of always on sensors (e.g., video sensors, mobile sensors, static sensors) after data sensing, data storage and data processing, are transmitted first

- *This work was supported by a Four Year Doctoral Fellowship from The University of British Columbia and in part by funding from the Natural Sciences and Engineering Research Council of Canada, the ICICS/TELUS People & Planet Friendly Home Initiative at The University of British Columbia, TELUS and other industry partners. The work of L. Shu was supported by Project from Educational Commission of Guangdong Province of China under Grant 2013KJCX0131 and 2013 Special Fund of Guangdong Higher School Talent Recruitment.*
- *C. Zhu, Z. Sheng and V. C. M. Leung are with the Department of Electrical and Computer Engineering, The University of British Columbia, Vancouver, BC, Canada V6T 1Z4 (e-mail: {cszhu, zhengguo, vleung}@ece.ubc.ca).*
- *L. Shu is with the Guangdong Provincial Key Lab. of Petrochemical Equipment Fault Diagnosis, Guangdong University of Petrochemical Technology, Maoming, Guangdong 525000 China (e-mail: lei.shu@lab.gdupt.edu.cn).*
- *L. T. Yang is with the Department of Computer Science, St. Francis Xavier University, Antigonish, NS, Canada B2G 2W5 (e-mail: ltyang@stfx.ca).*

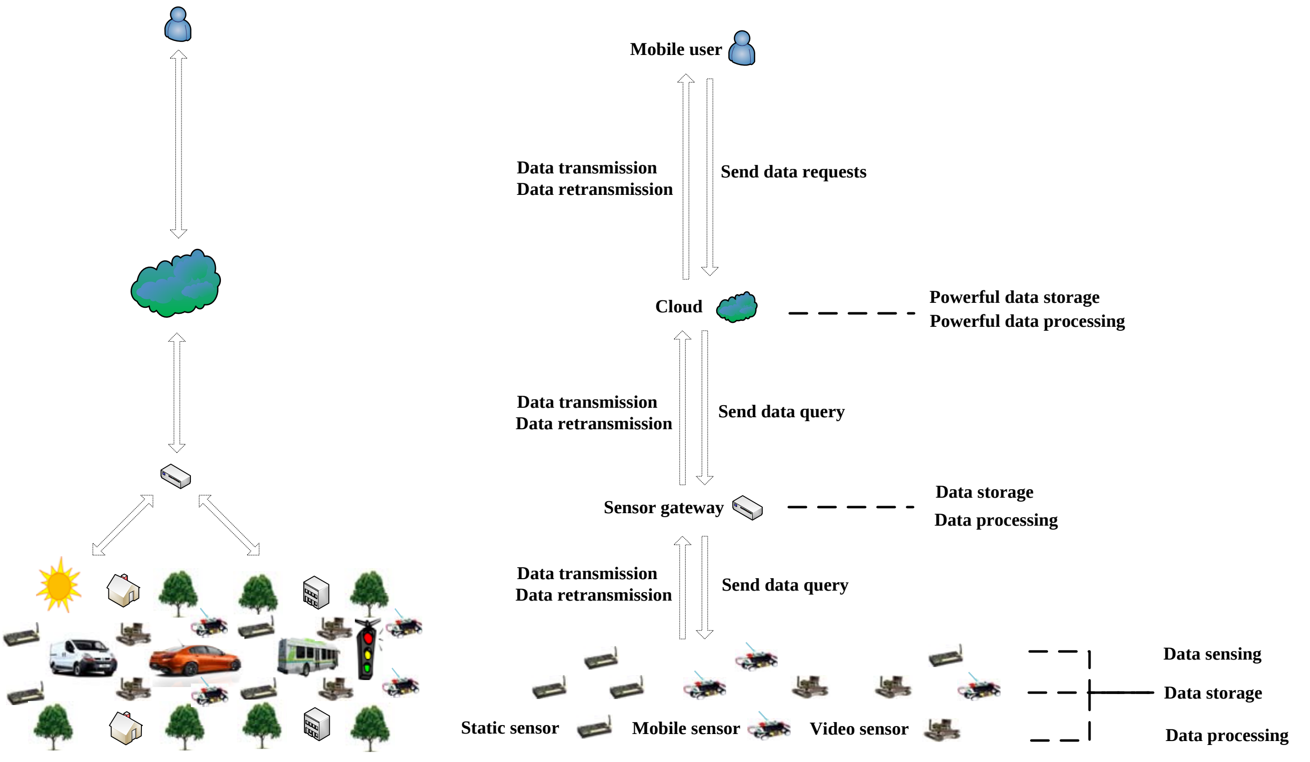

Fig. 1. General scheme (GS) to gather and transmit sensory data for WSN-MCC integration

to the WSN gateway in a hop-by-hop manner. The gateway then further stores, processes and transmits the received sensory data to the cloud. Finally, the cloud stores, processes and transmits the sensory data to mobile users on demand. During the whole data transmission process, if the data transmissions from the sensor nodes to the gateway or from the gateway to the cloud or from the cloud to the mobile user are not successful, data are retransmitted until they are successfully delivered.

For this new WSN-MCC integration paradigm, the WSN acts as the data source for the cloud and mobile users are the data requesters for the cloud. With just a simple client on their mobile devices, mobile users can have access to their required sensory data from the cloud, whenever and wherever there is network connection. Evolving as the concept of "sensor-cloud", the integrated WSN-MCC is "an infrastructure that allows truly pervasive computation using sensors as an interface between physical and cyber worlds, the data-compute clusters as the cyber backbone and the internet as the communication medium" [13] [14].

1.2 Research motivation

In these potential applications of integrated WSN-MCC (e.g., ubiquitous healthcare monitoring, environmental monitoring for disaster detection, agriculture and irrigation control, earth observation, transportation and vehicle real-time visualization, tunnel monitoring, wildlife monitoring) [15], quite a number of them actually require the WSN to reliably offer sensory data that are more useful to the cloud based on the requests of the mobile users.

Take smart house monitoring as an instance, although various monitored information about the whole house gathered by the strategically deployed video sensors, image sensors and other types of sensors can be offloaded to the cloud to let the owner of the house or other authenticated and permitted people conveniently access their desired data with the mobile devices (e.g., smart phones, tablet computers), it is expected that videos from some locations (e.g., storage room) are of little interest, while videos from other locations (e.g., front door, back door, windows) are considered to be more important to make sure that there is no unexpected intrusion into the house.

Thus, not all the sensory data are useful (i.e., actually utilized) for the cloud to satisfy user requests, while transmitting these data (i.e., multimedia data) to the cloud will use substantial network bandwidth. From this point, we can observe that 1) sensory data that are more useful to the mobile users should be offered from WSN to cloud. On the other hand, to perform the goal of monitoring the house intelligently, the WSN needs to successfully gather and transmit the collected information (e.g., videos, images) to the cloud continuously, which means that 2) the sensory data should be reliably offered from the WSN to the cloud.

1.3 Research contribution and organization

In this paper, to support these WSN-MCC integration applications that require WSN to reliably collect and send data that are more useful to the mobile users to cloud, we first identify the critical issues that affect the usefulness of sensory data and reliability of WSN, and then propose a novel WSN-MCC integration scheme named TPSS. Specifically, TPSS includes two parts: 1) TPSDT (Time and Priority based Selective Data Transmission) for WSN gateway to selectively transmit sensory data that are more useful to the cloud, considering the time and priority features of the data requested by the mobile user; 2) PSS (Priority-based Sleep Scheduling) algorithm for WSN to save energy consumption so that it can gather and transmit data in a more reliable way. Analytical and experimental results demonstrate the effectiveness of TPSS, in enhancing the usefulness of sensory data and reliability of WSN for WSN-MCC integration.

The main contributions of this paper are summarized as follows.

- This paper is the first work that investigates jointly the issues regarding usefulness of sensory data and reliability of WSN from the viewpoint of WSN-MCC integration.
- This paper further proposes a novel TPSS scheme consisting of TPSDT and PSS for WSN-MCC integration, aimed respectively at improving the usefulness of sensory data and reliability of WSN. Specifically, TPSDT is utilized by WSN gateway to selectively transmit sensory data that are more useful to the cloud. In addition, PSS is used by WSN to save energy consumption for gathering and transmitting data resulting in a more reliable operation. Both TPSDT and PSS take the time and priority features of the data requested by the mobile user into account.

In the rest of this paper, the issues concerning the usefulness of sensory data and reliability of WSN with respect to WSN-MCC integration are discussed in Section 2. Section 3 introduces the WSN-MCC integration system model and Section 4 presents TPSDT and PSS, which are the two main components of TPSS. The proposed TPSS is analyzed in Section 5. Section 6 evaluates TPSS with experimental results. Related works about WSN-MCC integration are reviewed in Section 7. Section 8 concludes this paper.

2 USEFULNESS OF SENSORY DATA AND RELIABILITY OF WSN

2.1 Usefulness of sensory data

In the context of WSN-MCC integration, this paper considers the usefulness of sensory data according to whether the sensory data offered by the WSN is eventually utilized by the cloud to satisfy the data requests from mobile users. We observe that characteristics of user data requests are key factors that affect the usefulness of sensory data.

2.1.1 User data request characteristics

The behavior that a user issues data requests to the cloud is usually characterized by *Time* [16] [17]. For example, it is very common in our daily life that "usually someone (say, Bob) will do something (say, watch a talk show) with some mobile device during some time period (e.g., 2:00 pm to 3:00 pm)". In addition, the content of the data requested by a user usually has *Priority* [17] [18]. For instance, although the traffic information of the whole city has some value to a certain extent, a lot of mobile users may be more interested in the traffic information of the downtown than the traffic information in a quiet countryside during the same time period. Meanwhile, a substantial number of mobile users may only be interested in the traffic information of a certain set of places (e.g., company, living residence, restaurant, school) among all the places in the city.

In short, the transmitted data from the WSN to the cloud may not be fully utilized by the cloud to satisfy the mobile users' data requests, as mobile users generally issue data requests for some certain contents for a specific time period. Thus, it is not necessary for the WSN to always transmit all the sensory data to the cloud, since it is not efficient and it also increases the transmission bandwidth requirement and exacerbates the network traffic.

However, all sensory data still need to be able to be collected by sensors, as mobile users may request data from any sensor at any time, though with highly varied probabilities. In this paper, since usually the data request behaviors of mobile users are characterized by time and priority and there are various factors (e.g., communication interference, network congestion, limited bandwidth) [19] [20] that affect the data gathering and data transmission latency, we ignore the issue regarding latency of gathering and transmitting data to satisfy data requests from mobile users.

2.2 Reliability of WSN

In WSN-MCC integration, one aspect of WSN reliability relates to whether the WSN is continuously able to gather and transmit the sensory data to the cloud successfully. We observe the following critical issues concerning the reliability of WSN.

2.2.1 Depletion of sensor energy

Generally, sensors will deplete their limited battery power by performing data sensing, processing and transmission after a certain period of time, as they are often equipped with batteries that are not rechargeable and battery replacement may also be impractical [21] [22]. Particularly, the sensors close to the gateway are serving as intermediary nodes that forward most packets to the gateway on behalf of the source nodes. Therefore they may deplete their energy sooner than other sensors and form holes in the WSN where no data can be collected for the cloud, or cause the WSN to be disconnected.

2.2.2 Failures in sensory data transmissions

The data transmissions from one sensor to another sensor and from the WSN to the cloud may encounter failures or losses, due to various factors such as network congestion, limited bandwidth or interference [19] [23]. In such cases, if the WSN does not perform data retransmission, then the cloud cannot obtain the sensory data coming from the WSN. In this paper, we consider that this reliability issue is always overcome through data retransmissions.

2.2.3 Limit in storage space for sensory data

As stated in [24], data storage is a very serious issue for WSN, since a large volume of collected data needs to be archived for future information retrieval. In addition, when sensors are deployed to gather multimedia data such as images or videos that usually have large sizes, this further aggravates the demand on sensory data storage space. If the sensors do not have available storage space to store the sensed data, then the cloud cannot obtain any sensory data, even if the sensors have enough residual energy to gather and transmit data and the data transmissions from WSN to cloud are successful. In this paper, we assume that sensors have sufficient storage space.

In this paper, we do not consider the sensory data transmission failure and sensory data storage space limit issues for reasons given above, but instead focus on the sensor energy depletion issue, which strongly affects the reliability of a WSN.

3 WSN-MCC INTEGRATION SYSTEM MODEL

The WSN-MCC integration system is modeled and analyzed in this paper based on the following assumptions.

- There is one cloud C and M mobile users (i.e., $U = (u_1, u_2, \ldots, u_M)$) as well as M WSNs (i.e., $WSN = (wsn_1, wsn_2, \ldots, wsn_M)$). Each WSN gathers and transmits data to the cloud to satisfy the data requests from each corresponding mobile user.
- Each WSN consists of one gateway g as well as N sensor nodes (i.e., $I = (i_1, i_2, \ldots, i_N)$).
- Each gateway g is externally powered with an unlimited energy supply. Each sensor node i has a limited energy supply powered by a non-rechargeable and non-replaceable battery, which has an initial energy e_o and a residual energy e_i.
- Time is divided into Z time periods (i.e., $T = (t_1, t_2, \ldots, t_Z)$).

4 TPSDT AND PSS

In this section, we present and discuss the proposed 1) TPSDT mechanism for WSN gateway to selectively transmit sensory data that are more useful to the cloud and 2) PSS mechanism for WSN to save energy consumption so that it can gather and transmit data in a more reliable way.

4.1 TPSDT

The difference between our proposed TPSDT and other selective data transmission methods (e.g., [25] [26] [27]) in WSN is that TPSDT is the first method for WSN gateway to selectively transmit data to the cloud, considering the time and priority characteristics of the data requested by the mobile user. These characteristics are recorded in a Point vs Time & Priority (PTP) table maintained in the cloud for each mobile user, where each point corresponds to a sensor node and the time reflects the specific time period and the priority reflects the probability that the mobile user requests data from the corresponding sensor node during that time period.

4.1.1 PTP table

Based on the time and priority features illustrated in Section 2 about mobile user data requests, we consider that the cloud is able to analyze the historical behaviors of mobile user data requests and then maintain a PTP table of each mobile user with respect to time and priority for sensor nodes of interest.

An example of this PTP table reflecting the interest of a mobile user is shown in Table 1. Specifically, the probability that the data requests correspond to each point of interest, as shown in the PTP table, represents the priority of the requested data to the mobile user. A higher probability connected to a given point in a specific time period means that the mobile user is more interested in that point and is more likely to issue data requests for the point in that specific time period.

Assume the number of data requests issued for a point of interest (e.g., sensor node i) during each specific time period t in the history is r_i^t. In addition, given that the number of data requests issued to all points for each specific time period t in the history is R^t. The probability (i.e., p_i^t) that the data requests concern the sensor node i in each specific time period t is calculated as follows.

$$p_i^t = \frac{r_i^t}{R^t} \tag{1}$$

In addition, for the whole WSN-MCC integration, there are Z time periods and N sensor nodes. Thus,

$$1 = \sum_{i=i_1}^{i=i_N} p_i^t \quad (t = t_1, t_2, \ldots, t_Z) \tag{2}$$

TABLE 1
Example of Point vs Time & Priority (PTP) table

Point of Interest	9:00 am-10:00 am	10:00 am-11:00 am	11:00 am-12:00 pm	12:00 pm-1:00 pm	...
i_1	10%	5%	20%	15%	...
i_2	20%	5%	0%	15%	...
i_3	20%	10%	0%	15%	...
i_4	10%	10%	0%	10%	...
i_5	20%	20%	0%	15%	...
i_6	10%	20%	30%	15%	...
i_7	5%	20%	40%	5%	...
i_8	0%	5%	0%	5%	...
...	...	...	...	...	...

This PTP table obtained for each mobile user is updated dynamically by the cloud C and sent to the gateway g of each corresponding WSN.

4.1.2 Details of TPSDT

With the PTP table, the process of our proposed TPSDT for each WSN gateway to selectively transmit data that are more useful to the cloud is shown as follows.

- 1) Each gateway g sets a timer, which records the current time.
- 2) For each time period t, each gateway g sends the sensory data to the cloud C, according to the start time and end time of t in the PTP table.
- 3) Particularly, for the transmitted data content, each gateway g sends the sensory data gathered by each sensor node in order, according to the priorities (i.e., probabilities in the PTP table). The sensory data gathered by the points of interest with larger priorities are sent first, followed with sensory data collected by those with lower priorities. The sensory data coming from the points of interest with no priority (i.e., probability is 0%) in the PTP table are not transmitted.

4.2 PSS

The difference between our proposed PSS and other sleep scheduling algorithms (e.g., [28] [29] [30] [31]) in WSN is that PSS first incorporates the time and priority characteristics of the data requested by the mobile user into the WSN sleep scheduling process to gather and transmit data for the cloud, with PTP table.

4.2.1 Design factors

The design of the proposed PSS algorithm considers the following three factors: 1) the points of interest (i.e., sensor nodes of interest in WSN) in the PTP table with probability larger than 0% should be awake in each time period t, since mobile user requires sensory data gathered by these sensor nodes; 2) the whole sleep scheduled network should be connected so that data transmissions from sensor nodes to gateway can be performed; 3) only a subset of all sensor nodes should be awake in each time period t to reduce energy consumption - the sensor nodes that are scheduled to be awake should generally have more residual energy than the nodes that are scheduled to be asleep, so that network lifetime could be further prolonged.

4.2.2 Details of PSS

Considering the above three design factors, the pseudocode of the proposed PSS algorithm is shown as follows.

Pseudocode of PSS algorithm

First: Run the following at gateway g during each time period t.

Step 1: Gateway g obtains PTP table.
Step 2: If $p_i^t > 0$, g sends flag A to node i.
Step 3: Run the second part at each node i.

Second: Run the following at each node i during each time period t.

Step 1: Get the current residual energy rank e_i.
Step 2: Broadcast e_i and receive the energy ranks of its currently awake neighbors N_i. Let E_i be the set of these ranks.
Step 3: Broadcast E_i and receive E_j from each $j \in N_i$.
Step 4: If $|N_i| < k$ or $|N_j| < k$ for any $j \in N_i$, remain awake. Go to Step 7.
Step 5: Compute $C_i = \{j | j \in N_i \text{ and } e_j > e_i\}$.
Step 6: Go to sleep if both the following conditions hold. Remain awake otherwise.
- Any two nodes in C_i are connected either directly themselves or indirectly through nodes within i's 2-hop neighborhood that have e more than e_i.
- Any node in N_i has at least k neighbors from C_i.
- It does not receive flag A.

Step 7: Return.

4.2.3 Analysis of PSS

Property 1: The PSS algorithm guarantees that sensor nodes required to satisfy the anticipated data requests of mobile users are awake.

Discussion: We discuss this property by observing the execution process of PSS. Particularly, with respect to the sensor nodes from which mobile users require data, these sensor nodes are actually the points of interest in the PTP table with the corresponding probabilities larger than 0% (i.e., $p_i^t > 0$). From step 2 of the first part of PSS, we can observe that sensor node i will receive flag A if $p_i^t > 0$. Further, with step 6 of the second part of PSS, sensor nodes that receive the flag A cannot be asleep. In other words, sensor nodes receiving flag A will all be awake so as to gather and transmit data requested by the mobile users.

Property 2: PSS algorithm maintains a connected network if the original network is connected.

Discussion: We discuss this property by contradiction [28] [29] [30]. Given that the sleep scheduled network after running the PSS is not connected. Then, we put the deleted nodes (asleep nodes determined by PSS) back in the network, in descending order of their energy ranks. Let i be the first sensor node making the network connected again. Note that by the time we put i back, all the members of C_i are already present and sensor nodes in C_i are already connected since they are connected by nodes with $e > e_i$. Let v be a node that was disconnected from C_i but now is connected to C_i by i. Then, this contradicts the fact that i can sleep only if all its neighbors (including v) are connected to $\geq k$ nodes in C_i (Step 6 of the second part of PSS).

Property 3: The PSS algorithm prolongs the network lifetime compared with the always-on WSN.

Discussion: We discuss this property by analyzing the execution results after running PSS algorithm. First, from the entire steps of PSS, we can observe that after PSS, there is a subset of sensor nodes that determine to be awake and there is another subset of sensor nodes that are asleep. As only a subset of sensor nodes need to be awake, the energy consumption will be saved and the network lifetime will be prolonged, compared with the always on WSN scheme in which all sensors are always awake.

Second, based on step 6 of the second part of PSS, we can observe that after PSS, the asleep sensor nodes satisfy that 1) Any two nodes in C_i are connected either directly themselves or indirectly through nodes within i's 2-hop neighborhood that have e more than e_i. This constraint means that the awake nodes own more residual energy than the asleep sensor nodes after sleep scheduling. By letting the sensor nodes with more residual energy rather than the sensor nodes with less residual energy be awake to perform data sensing, data storage and data processing, the network lifetime is further prolonged.

5 Proposed TPSS WSN-MCC Integration Scheme

5.1 Overview

Fig. 2 shows the proposed TPSS scheme to gather and transmit sensory data for WSN-MCC integration, towards reliably offering data which are more useful to the mobile users from WSN to cloud. The detailed steps of TPSS for each WSN to gather and transmit sensory data for each corresponding mobile user are depicted as follows.

- 1) Sensor nodes determine their awake and asleep states with PSS.
- 2) Sensor nodes sense the environmental data with a set frequency and store the sensory data as well as process the sensory data.
- 3) Sensor nodes send the processed sensory data to the gateway g with the many to one and hop by hop pattern.
- 4) Gateway g stores the received sensory data and then processes the sensory data.
- 5) Gateway g selectively transmits the sensory data to the cloud C with TPSDT.
- 6) Cloud C further stores and processes the received sensory data.
- 7) If data transmission from i to g or g to C experiences data losses or failures, i or g performs data retransmission until the data transmission is successful.
- 8) Mobile user u issues data requests to cloud C and cloud C transmits the requested sensory data to the mobile user u.
- 9) If data transmission from C to u encounters data losses or failures, C performs data retransmission until the data transmission is successful.
- 10) Cloud C dynamically updates the PTP table with equation (1) if the time and priority features of the requested data of the mobile user are changed and sends the updated PTP table to gateway in each time period t.

5.2 Scheme characteristics and analysis

Comparing Fig. 1 and Fig. 2, based on the above introductions, we can see that our proposed TPSS shares the same technique with GS (i.e., data retransmission) to mitigate data transmission losses or failures in sensory data transmissions for improving the reliability of WSN during WSN-MCC integration.

In addition, we can observe that TPSS differs from GS to gather and transmit sensory data for WSN-MCC integration, with respect to the following two aspects.

5.2.1 *TPSDT for WSN gateway*

In our proposed TPSS, the gateway g selectively transmits the sensory data to the cloud C with TPSDT.

This design is to enhance the usefulness of sensory data, since TPSDT data transmission is based on the PTP table deduced from the time and priority features of the data requested by the mobile user. Thus, normally the successfully transmitted sensory data to the cloud will all be utilized to answer mobile user data requests.

In the case that the mobile user u issues data requests for sensory data currently not stored in the cloud C in the time period t, as the PTP table is dynamically updated with equation (1) if the time and priority features of the requested data of the mobile user are changed in t (Step 10 of the TPSS), running the PSS algorithm with the updated PTP table in t makes the sensor nodes from which mobile user requires data awake (property 1 of PSS). In other words, the cloud is capable of answering the unexpected data requests by dynamically updating PTP table.

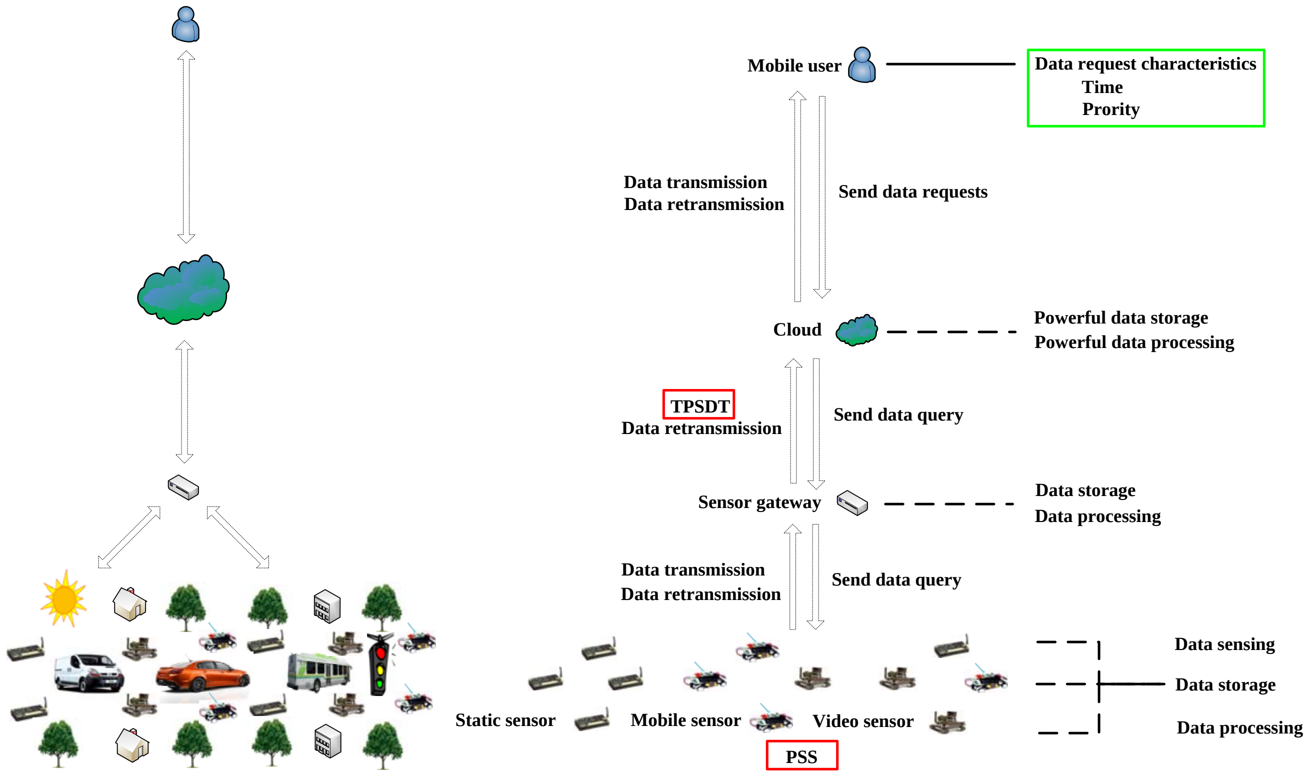

Fig. 2. Proposed TPSS scheme to gather and transmit sensory data for WSN-MCC integration

Moreover, as the sensory data are selectively transmitted from WSN gateway to the cloud with TPSDT, the bandwidth requirement and network congestion are reduced meanwhile. This can also enhance the reliability of WSN, as it alleviates the data transmission loss failure or loss issue to some extent.

5.2.2 PSS for WSN

In our proposed TPSS, the sensor nodes dynamically determine their awake and asleep states according to PSS.

This design can greatly improve the reliability of WSN, since PSS can greatly save the energy consumption and prolong the network lifetime (property 3 of PSS) so that WSN can gather and transmit data longer. Specifically, when sensors normally work for a certain period of time, the energy of the sensors will be consumed very fast and sensor nodes will die and cannot work any more. With PSS, sensor nodes are dynamically awake and asleep and only a subset of sensor nodes with more residual energy are required to be awake in each time period, this will greatly alleviate the sensory energy depletion issue that seriously affects the reliability of WSN and the lifetime of WSN will be greatly enhanced.

6 EVALUATIONS

6.1 Evaluation setup

To perform evaluations, we compare our proposed TPSS with GS to gather and transmit sensory data for WSN-MCC integration. Then we analyze whether our proposed TPSS is effective in enhancing the usefulness of sensory data and reliability of WSN.

6.1.1 WSN-MCC system

We assume that there is one cloud and 10 mobile users and 10 WSNs. Each WSN gathers and transmits data to the cloud, enabling it to reply to data requests from each corresponding mobile user. We further assume that each WSN consists of one gateway, which has an unlimited energy supply, and 100 sensor nodes, each of which has an initial energy of 100000 mJ. Time is divided into 24 time periods, each one hour long. The detailed evaluation parameters are summarized in Table 2.

6.1.2 Usefulness of sensory data

The usefulness of sensory data offered from a WSN to a cloud is evaluated, by analyzing how much the offered data from the WSN to the cloud is utilized to answer mobile user data requests, as illustrated in Section 2.

To analyze the usefulness of sensory data, the mobile user data request features (i.e., time and priority of the data requested by the mobile user) have to be obtained first. Regarding this, we perform the following experiment. We use a database resulting from 10 mobile users watching a surveillance video for three consecutive weeks from 10:00 am to 4:00

TABLE 2
Evaluation Parameters

Parameter	Parameter value
Number of clouds	1
Number of users	10
Number of WSNs	10
Number of sensor nodes	100
Number of gateways	1
Initial sensor energy	100000 mJ
Time period	1 hour
Network size	800×600 m^2
Default transmission radius	60 m
Transmission energy	0.0144 mJ
Reception energy	0.00576 mJ
Transmission amplifier energy	0.0288 nJ/m^2
Packet length	12 bytes
Number of packets	1000
k in PSS	1

pm. For each day, we observe the time and priority of the data requested by the mobile users and they are transformed to different PTP tables. Then the same 10 mobile users watch the same surveillance video for another three consecutive weeks from 10:00 am to 4:00 pm and we analyze the usefulness of sensory data offered by TPSS and GS with the following assumptions.

For TPSS, we assume that the PTP tables are maintained by the cloud and further utilized by WSN gateways to transmit sensory data to the cloud with TPSDT for the 10 mobile users. For GS, we assume that the WSN gateways will transmit all sensory data to the cloud for the 10 mobile users, without utilizing the PTP tables. With that, the usefulness of sensory data which is actually the utility of the sensory data offered from the WSN to the cloud for each mobile user, could be respectively obtained for TPSS and GS as follows. Regarding TPSS, we analyze the percentage that the time and priority of the requested data of each mobile user observed in the previous three consecutive weeks are also observed in the subsequent three consecutive weeks. Regarding GS, we directly obtain the utility of the sensory data offered from the WSN to the cloud for each mobile user, by comparing the whole surveillance video with the content that each mobile user requests in the subsequent three consecutive weeks. The average utility of the sensory data offered from WSN to the cloud for each mobile user in each week is taken as the average usefulness of sensory data for each mobile user in each week.

6.1.3 Reliability of WSN

The reliability of WSN is evaluated by analyzing how long the WSN is able to gather and transmit sensory data to the cloud, as illustrated in Section 2. Specifically, we observe the network lifetime of WSN. In this paper, the network lifetime of WSN is the time from the instant of network deployment to the instant when the first sensor node runs out of energy [32].

To analyze the reliability of WSN, we obtain the network lifetime of WSN in NetTopo [33], with each PTP table for each mobile user in the subsequent three consecutive weeks. For both TPSS and GS, the network size is 800×600 m^2 and the default transmission radius is 60 m. The energy consumed by a sensor to transmit and receive one byte are, respectively, 0.0144 mJ and 0.00576 mJ [22] [30] [34]. The energy consumed by a sensor to power-amplify each transmitted byte to cover the distance of 1 m is 0.0288 nJ/m^2 [22] [30] [34]. The packet length is 12 bytes and there are 1000 packets transmitted during the communication time of each node [22] [30] [34]. The k in PSS is 1, which is the minimum value of k in PSS. The average value of the network lifetime of WSN gathering and transmitting data for each mobile user in each week is taken as the average reliability of WSN for each mobile user in each week.

6.2 Evaluation results

The evaluation results with respect to usefulness of sensory data and reliability of WSN for each mobile user in each week are shown in Fig. 3 and Fig. 4, respectively.

From Fig. 3, we can observe that, averaging over all mobile users, around 85% of the sensory data sent to the cloud with TPSS are useful to the mobile users, whereas only around 45% of the sensory data sent to the cloud with GS are useful to the mobile users. The same results are obtained for each of the three weeks observed. This demonstrates that TPSS greatly improves the usefulness of sensory data due to the fact that mobile users generally request data over time according to the PTP tables.

From Fig. 4, we can observe that the reliability of WSN is also greatly enhanced with TPSS comparing GS. Particularly, the three sub-figures show that over each of the three weeks observed, the reliability of WSN with GS is around 180 hours for all the mobile users, while the reliability of WSN with TPSS varies among different mobile users but averages to around 400 hours.

In summary, TPSS substantially outperforms GS in terms of usefulness of sensory data and reliability of WSN. Moreover, for different mobile users with various data request characteristics indicated by different PTP tables, the usefulness of sensory data varies considerably for both TPSS and GS, as indicated in Fig. 3, while only the reliability of WSN for TPSS changes with mobile users as shown in Fig. 4.

7 Related work

There are a number of works related to WSN-MCC integration. They mainly focus on the following two aspects: 1) improving the performance of WSN, and 2) better utilizing the data collected by the WSN.

Specifically, with respect to 1) improving the performance of WSN with WSN-MCC integration, it is

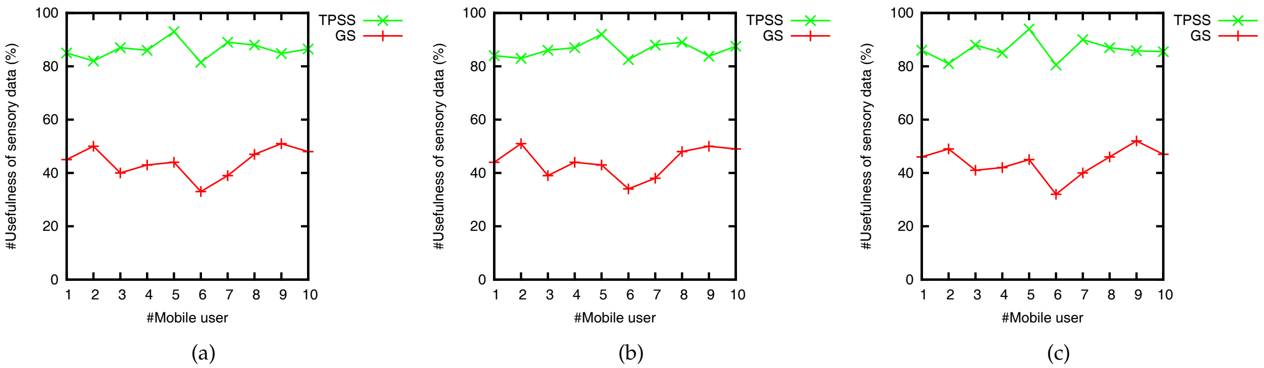

Fig. 3. Average usefulness of sensory data for each mobile user in week 1 (a); in week 2 (b) and in week 3 (c).

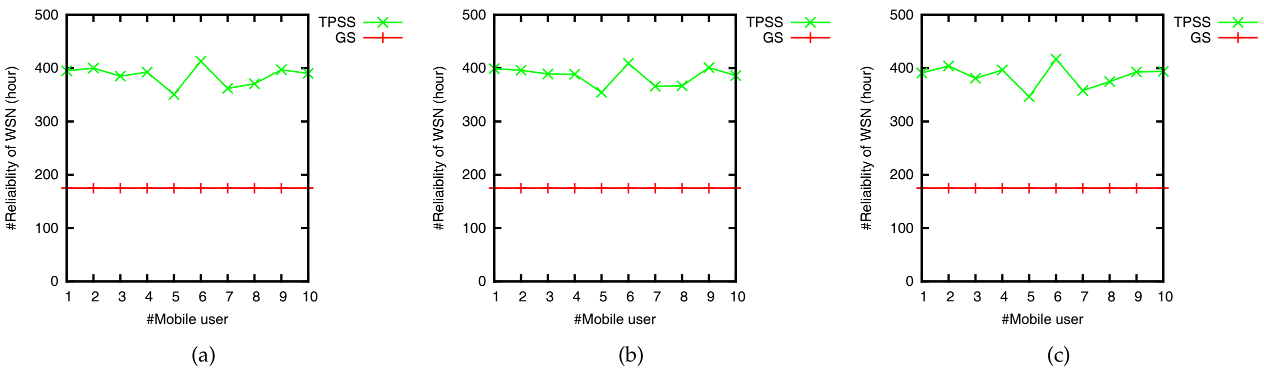

Fig. 4. Average reliability of WSN for each mobile user in week 1 (a); in week 2 (b) and in week 3 (c).

argued in [35] that the integration of WSN and MCC is able to support the dynamic loads that are generated by environmental WSN applications. It is demonstrated in [36] that the integration of WSN and MCC could address the challenge of data management in WSN for patient supervision. Moreover, it is suggested in [37] that the cloud could potentially enhance the visualization performance of a WSN for living environments. A collaborative location-based sleep scheduling algorithm is proposed in [38] to improve the network lifetime performance of the integrated WSN. This algorithm addresses the WSN reliability issue to some extent by extending the network lifetime. However, the usefulness of sensory data is not considered.

In addition, about 2) better utilizing the data collected by the WSN with WSN-MCC integration, the focus of [39] is to propose a framework to utilize the ever-expanding sensory data for various next generation community-centric sensing applications on the cloud. Similarly, the motivation of [40] is to facilitate the shift of data from the WSN to the cloud computing environment so that the scientifically and economically valuable WSN data may be fully utilized. Moreover, a cloud design for user-controlled storage and processing of sensory data is proposed in [41] to make data owners trust that the management of the sensitive data is secure. Finally, [42] puts forward a framework providing desirable sensory data to users faster with data analysis techniques, so that the sensory data could be better utilized with cloud computing.

To the best of our knowledge, currently there is no research work focusing jointly on issues about the usefulness of sensory data and reliability of WSN in WSN-MCC integration. Our proposed TPSS is the first work that considers together the usefulness of sensory data and reliability of WSN for WSN-MCC integration. Particularly, TPSS incorporates TPSDT and PSS to improve both the usefulness of sensory data and reliability of WSN.

8 Conclusion

In this paper, we have focused on WSN-MCC integration by incorporating the ubiquitous data gathering ability of WSN and the powerful data storage and data processing capabilities of MCC. Particularly, to support WSN-MCC integration applications that need more useful data offered reliably from the WSN to the cloud, we have identified the critical issues that impede the usefulness of sensory data and reliability of WSN, and proposed a novel WSN-MCC integration scheme named TPSS to address some of these issues. Specifically, TPSS consists of the following two main parts: 1) TPSDT for WSN gateway to selectively transmit sensory data that are more useful to the cloud, considering the time and priority features of the data requested by the mobile user; 2) PSS algorithm for WSN to save energy consumption so that it can gather and transmit data more reliably. Both analytical and experimental results regarding TPSS have been presented to demonstrate the effectiveness of TPSS in improving the usefulness of sensory data and reliability of WSN for WSN-MCC integration.

REFERENCES

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Comput. Netw.*, vol. 38, no. 4, pp. 393–422, Mar. 2002.

[2] M. Li and Y. Liu, "Underground coal mine monitoring with wireless sensor networks," *ACM Trans. Sens. Netw.*, vol. 5, no. 2, Mar. 2009.

[3] C. Zhu, L. Shu, T. Hara, L. Wang, S. Nishio, and L. T. Yang, "A survey on communication and data management issues in mobile sensor networks," *Wirel. Commun. Mob. Comput.*, vol. 14, no. 1, pp. 19–36, Jan. 2014.

[4] C. Zhu, V. C. M. Leung, X. Hu, L. Shu, and L. T. Yang, "A review of key issues that concern the feasibility of mobile cloud computing," in *Proc. IEEE Int. Conf. Cyber, Phys. and Soc. Comput. (CPSCom)*, 2013, pp. 769–776.

[5] S. Abolfazli, Z. Sanaei, M. Alizadeh, A. Gani, and F. Xia, "An experimental analysis on cloud-based mobile augmentation in mobile cloud computing," *IEEE Trans. Consum. Electron.*, vol. 60, no. 1, pp. 146–154, Feb. 2014.

[6] A. R. Khan, M. Othman, S. A. Madani, and S. U. Khan, "A survey of mobile cloud computing application models," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 1, pp. 393–413, First Quarter 2014.

[7] A. Benharref and M. A. Serhani, "Novel cloud and soa-based framework for e-health monitoring using wireless biosensors," *IEEE J. Biomed. Health Inform.*, vol. 18, no. 1, pp. 46–55, Jan. 2014.

[8] L. D. P. Mendes, J. J. P. C. Rodrigues, J. Lloret, and S. Sendra, "Cross-layer dynamic admission control for cloud-based multimedia sensor networks," *IEEE Syst. J.*, vol. 8, no. 1, pp. 235–246, Mar. 2014.

[9] S. Madria, V. Kumar, and R. Dalvi, "Sensor cloud: A cloud of virtual sensors," *IEEE Softw.*, vol. 31, no. 2, pp. 70–77, Mar.-Apr. 2014.

[10] S. Misra, S. Bera, A. Mondal, R. Tirkey, H.-C. Chao, and S. Chattopadhyay, "Optimal gateway selection in sensor-cloud framework for health monitoring," *IET Wirel. Sens. Syst.*, vol. 4, no. 2, pp. 61–68, Jun. 2014.

[11] S. T. Ali, V. Sivaraman, and D. Ostry, "Authentication of lossy data in body-sensor networks for cloud-based healthcare monitoring," *Future Generation Comput. Syst.*, vol. 35, pp. 80–90, Jun. 2014.

[12] S. Chatterjee and S. Misra, "Target tracking using sensor-cloud: Sensor-target mapping in presence of overlapping coverage," *IEEE Commun. Lett.*, vol. 18, no. 8, pp. 1435–1438, Aug. 2014.

[13] *http://www.ntu.edu.sg/intellisys*.

[14] K.-L. Tan, "What's next?: Sensor + cloud!?" in *Proc. 7th Int. Workshop on Data Manage. for Sens. Netw. (DMSN)*, 2010.

[15] A. Alamri, W. S. Ansari, M. M. Hassan, M. S. Hossain, A. Alelaiwi, and M. A. Hossain, "A survey on sensor-cloud: Architecture, applications, and approaches," *Int. J. Distrib. Sens. Netw.*, pp. 1–18, 2013.

[16] F. Wang, J. Liu, and M. Chen, "Calms: Cloud-assisted live media streaming for globalized demands with time/region diversities," in *Proc. IEEE Int. Conf. Comput. Commun. (Infocom)*, 2012, pp. 199–207.

[17] B. Pan, X. Wang, C.-P. Hong, and S.-D. Kim, "Amvp-cloud: A framework of adaptive mobile video streaming and user behavior oriented video pre-fetching in the clouds," in *Proc. IEEE 12th Int. Conf. Comput. Inf. Technol. (CIT)*, 2012, pp. 398–405.

[18] A. M. Riad, M. Elmogy, and A. I. Shehab, "A framework for cloud p2p vod system based on user's behavior analysis," *Int. J. Comput. Appl.*, vol. 76, no. 6, pp. 20–26, Aug. 2013.

[19] F. Hu, Y. Xiao, and Q. Hao, "Congestion-aware, loss-resilient bio-monitoring sensor networking for mobile health applications," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 4, pp. 450–465, May 2009.

[20] W. Fang, F. Liu, F. Yang, L. Shu, and S. Nishio, "Energy-efficient cooperative communication for data transmission in wireless sensor networks," *IEEE Trans. Consum. Electron.*, vol. 56, no. 4, pp. 2185–2192, Nov. 2010.

[21] C. Zhu, H. Wang, X. Liu, L. Shu, L. T. Yang, and V. C. M. Leung, "A novel sensory data processing framework to integrate sensor networks with mobile cloud," *IEEE Syst. J.*, 2014.

[22] C. Zhu, V. C. M. Leung, L. T. Yang, and L. Shu, "Collaborative location-based sleep scheduling for wireless sensor networks integrated with mobile cloud computing," *IEEE Trans. Comput.*, 2014.

[23] W. Fang, J. Chen, L. Shu, T. Chu, and D. Qian, "Congestion avoidance, detection and alleviation in wireless sensor networks," *J. Zhejiang Univ. Sci. C*, vol. 11, no. 1, pp. 63–73, Jan. 2010.

[24] B. Sheng, Q. Li, and W. Mao, "Optimize storage placement in sensor networks," *IEEE Trans. Mobile Comput.*, vol. 9, no. 10, pp. 1437–1450, Oct. 2010.

[25] R. Arroyo-Valles, A. G. Marques, and J. Cid-Sueiro, "Optimal selective transmission under energy constraints in sensor networks," *IEEE Trans. Mobile Comput.*, vol. 8, no. 11, pp. 1524–1538, Nov. 2009.

[26] G. Battistelli, A. Benavoli, and L. Chisci, "Data-driven strategies for selective data transmission in sensor networks," in *Proc. IEEE 51st Annu. Conf. Decis. Control (CDC)*, 2012, pp. 800–805.

[27] R. Arroyo-Valles, A. G. Marques, and J. Cid-Sueiro, "Optimal selective forwarding for energy saving in wireless sensor networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 1, pp. 164–175, Jan. 2011.

[28] S. Nath and P. B. Gibbons, "Communicating via fireflies: Geographic routing on duty-cycled sensors," in *Proc. Int. Conf. Inf. Process. Sens. Netw. (IPSN)*, 2007, pp. 440–449.

[29] C. Zhu, L. T. Yang, L. Shu, J. J. P. C. Rodrigues, and T. Hara, "A geographic routing oriented sleep scheduling algorithm in duty-cycled sensor networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, 2012, pp. 7001–7005.

[30] C. Zhu, L. T. Yang, L. Shu, V. C. M. Leung, J. J. P. C. Rodrigues, and L. Wang, "Sleep scheduling for geographic routing in duty-cycled mobile sensor networks," *IEEE Trans. Ind. Electron.*, vol. 61, no. 11, pp. 6346–6355, Nov. 2014.

[31] C. Zhu, L. T. Yang, L. Shu, T. Q. Duong, and S. Nishio, "Secured energy-aware sleep scheduling algorithm in duty-cycled sensor networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, 2012, pp. 1953–1957.

[32] Y. T. Hou, Y. Shi, and H. D. Sherali, "Rate allocation and network lifetime problems for wireless sensor networks," *IEEE/ACM Trans. Netw.*, vol. 16, no. 2, pp. 321–334, Apr. 2008.

[33] L. Shu, M. Hauswirth, H.-C. Chao, M. Chen, and Y. Zhang, "Nettopo: A framework of simulation and visualization for wireless sensor networks," *Ad Hoc Netw.*, vol. 9, no. 5, pp. 799–820, Jul. 2011.

[34] C. Zhu, L. T. Yang, L. Shu, V. C. M. Leung, T. Hara, and S. Nishio, "Insights of top-k query in duty-cycled wireless sensor networks," *IEEE Trans. Ind. Electron.*, 2014.

[35] K. Lee, D. Murray, D. Hughes, and W. Joosen, "Extending sensor networks into the cloud using amazon web services," in *Proc. IEEE Int. Conf. Netw. Embedded Syst. Enterp. Appl. (NESEA)*, 2010, pp. 1–7.

[36] A. Lounis, A. Hadjidj, A. Bouabdallah, and Y. Challal, "Secure and scalable cloud-based architecture for e-health wireless sensor networks," in *Proc. 21st Int. Conf. Comput. Commun. Netw. (ICCCN)*, 2012, pp. 1–7.

[37] Y. Takabe, K. Matsumoto, M. Yamagiwa, and M. Uehara, "Proposed sensor network for living environments using cloud computing," in *Proc. 15th Int. Conf. Netw.-Based Inf. Sys. (NBiS)*, 2012, pp. 838–843.

[38] C. Zhu, V. C. M. Leung, L. T. Yang, X. Hu, and L. Shu, "Collaborative location-based sleep scheduling to integrate wireless sensor networks with mobile cloud computing," in *Proc. IEEE Globecom Workshop on Cloud Comput. Syst., Netw., and Appl. (CCSNA)*, 2013, pp. 451–456.

[39] M. M. Hassan, B. Song, and E.-N. Huh, "A framework of sensor - cloud integration opportunities and challenges," in *Proc. 3rd Int. Conf. Ubiquitous Inf. Manage. Commun. (ICUIMC)*, 2009, pp. 618–626.

[40] K. Ahmed and M. Gregory, "Integrating wireless sensor networks with cloud computing," in *Proc. 7th Int. Conf. Mob. Ad-hoc Sens. Netw. (MSN)*, 2011, pp. 364–366.

[41] R. Hummen, M. Henze, D. Catrein, and K. Wehrle, "A cloud design for user-controlled storage and processing of sensor data," in *Proc. IEEE 4th Int. Conf. Cloud Comput. Technol. Sci. (CloudCom)*, 2012, pp. 232–240.

[42] C. Zhu, V. C. M. Leung, H. Wang, W. Chen, and X. Liu, "Providing desirable data to users when integrating wireless sensor networks with mobile cloud," in *Proc. IEEE 5th Int. Conf. Cloud Comput. Technol. Sci. (CloudCom)*, 2013, pp. 607–614.

Chunsheng Zhu (S'12) received the B.E. degree in Network Engineering from Dalian University of Technology, China, in June 2010. And he obtained the M.Sc. degree in Computer Science from St. Francis Xavier University, Canada, in May 2012.

He is currently a PhD Student in the Department of Electrical and Computer Engineering at The University of British Columbia in Canada from September 2012. He has around 40 papers published or accepted by refereed international journals (e.g., IEEE Transactions on Industrial Electronics, IEEE Transactions on Computers, IEEE Systems Journal) and conferences (e.g., IEEE Globecom, IEEE ICC). His current research interests are mainly in the areas of wireless sensor networks and mobile cloud computing. He is a student member of IEEE.

Victor C. M. Leung (S'75-M'89-SM'97-F'03) received the B.A.Sc. (Hons.) degree in electrical engineering from the University of British Columbia (UBC) in 1977, and was awarded the APEBC Gold Medal as the head of the graduating class in the Faculty of Applied Science. He attended graduate school at UBC on a Natural Sciences and Engineering Research Council Postgraduate Scholarship and completed the Ph.D. degree in electrical engineering in 1981.

From 1981 to 1987, Dr. Leung was a Senior Member of Technical Staff and satellite system specialist at MPR Teltech Ltd., Canada. In 1988, he was a Lecturer in the Department of Electronics at the Chinese University of Hong Kong. He returned to UBC as a faculty member in 1989, and currently holds the positions of Professor and TELUS Mobility Research Chair in Advanced Telecommunications Engineering in the Department of Electrical and Computer Engineering. Dr. Leung has co-authored more than 750 technical papers in international journals and conference proceedings, 29 book chapters, and co-edited 8 book titles in the areas of wireless networks and mobile systems. Several of his papers had been selected for best paper awards.

Dr. Leung is a registered professional engineer in the Province of British Columbia, Canada. He is a Fellow of IEEE, the Royal Society of Canada, the Engineering Institute of Canada, and the Canadian Academy of Engineering. He was a Distinguished Lecturer of the IEEE Communications Society. He is serving on the editorial boards of the *IEEE Wireless Communications Letters*, *Computer Communications*, and several other journals, and has previously served on the editorial boards of the *IEEE Journal on Selected Areas in Communications - Wireless Communications Series*, *IEEE Transactions on Wireless Communications*, *IEEE Transactions on Vehicular Technology*, *IEEE Transactions on Computers*, and *Journal of Communications and Networks*. He has guest-edited many journal special issues, and contributed to the organizing committees and technical program committees of numerous conferences and workshops. He was a recipient of the IEEE Vancouver Section Centennial Award and 2012 UBC Killam Research Prize.

Zhengguo Sheng (M'11) is a Research Associate at The University of British Columbia, Canada. His current research projects cover machine-to-machine (M2M), mobile cloud computing, vehicular communications and wireless sensor networks. He was previously with France Telecom Orange Labs as the senior researcher and project manager in M2M and Internet-of-Things, as well as the coordinator of Orange and Asia telco on NFC-SWP partnership. He is also the winner of Orange Outstanding Researcher Award and CEO Retention bonus recipient, 2012. He also worked as a research intern with IBM T. J. Watson research centre USA and US Army Research labs. Before joining Orange Labs, he received his Ph.D. and M.S. degrees with distinction at Imperial College London in 2011 and 2007, respectively, and B.Sc. degree from University of Electronic Science and Technology of China (UESTC) in 2006.

He has published more than 20 technical papers in international journals and conference proceedings, co-edited 3 books and 2 standardization contributions in OMA and OneM2M. He is a member of the editorial boards of ELSEVIER Journals of Computer Communications (COMCOM), co-organizer of IEEE WiVeC 2014, and technical program committee member of Qshine 2014, ContextDD 2014.

Lei Shu (M'07) received the B.Sc. degree in Computer Science from South Central University for Nationalities, China, in 2002 and the M.Sc. degree in Computer Engineering from Kyung Hee University, Korea, in 2005 and the Ph.D. degree in Digital Enterprise Research Institute, from National University of Ireland, Galway, Ireland, in 2010.

He is currently a Full Professor in College of Electronic Information and Computer, Guangdong University of Petrochemical Technology, China, also the Vice-Director of the Guangdong Petrochemical Equipment Fault Diagnosis (PEFD) Key Laboratory. He was a Specially Assigned Research Fellow in Department of Multimedia Engineering, Graduate School of Information Science and Technology, Osaka University, Japan. He has published over 200 papers in related conferences, journals, and books. He had been awarded the Globecom 2010 and ICC 2013 Best Paper Award. He is serving as Editor in Chief for EAI Endorsed Transactions on Industrial Networks and Intelligent Systems, and he has served as editor and guest editor of more than 20 international journals. He has served as more than 50 various Co-Chair for international conferences/workshops, e.g., IWCMC, ICC, ISCC; TPC members of more than 150 conferences, e.g., ICC, Globecom, ICCCN, WCNC, ISCC. He has served as reviewer of more than 50 journals. His research interests include wireless sensor network, sensor network middleware, multimedia communication, and security. He is a member of IEEE and ACM.

Laurence T. Yang (M'97) received the B.E. degree in Computer Science and Technology from Tsinghua University, China, and the Ph.D. degree in Computer Science from University of Victoria, Canada.

He is a Professor in the Department of Computer Science, St. Francis Xavier University, Canada. His research interests include parallel and distributed computing, embedded and ubiquitous/pervasive computing, big data. He has published more than 200 papers in various refereed journals (around 1/3 on IEEE/ACM Transactions and Journals, others mostly on Elsevier, Springer and Wiley Journals). His research has been supported by the National Sciences and Engineering Research Council, and the Canada Foundation for Innovation.