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Energy-efficient sensing method for table grapes cold chain management

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ABSTRACT

Energy efficiency of the wireless sensor network (WSN) is one of the dominating issues in the non-stop table grapes cold chain monitoring. The aim of this paper is to propose an energy-efficient sensing method for the non-stop cold chain management of table grapes in order to reduce the average energy consumption of WSN devices and improve the operation and transmission efficiency of WSN, and finally strengthen the transparency, traceability and stabilization in non-stop cold chain monitoring. The energy-efficient sensing in non-stop cold chain monitoring was realized by combining the WSN and the CS transmission mode for the sensor data acquisition and transmission. According to the comprehensive analysis of the environmental performance, the CS performance, the energy consumption of WSN devices, the transmission efficiency and economic performance in actual cold chain of table grapes, the WSN with CS transmission mode could have the sensor data been transmitted with relatively few sampling amount and reconstructed with high accuracy and efficiency. The proposed energy-efficient sensing method could be extended for the non-stop cold chain monitoring applications to improve their energy, operation and transmission efficiency.

1. Introduction

Energy efficiency of the wireless sensor network (WSN) is one of the dominating issues in the broad range of WSN applications (Maleki et al., 2014), especially in non-stop table grapes cold chain monitoring. WSN provides a flexible way to monitor the environmental information in non-stop cold chain monitoring through a large number of spatially distributed sensor nodes (e.g. Carullo et al., 2009; Wang et al., 2015; Xiao et al., 2017). According to Ngcobo et al. (2013) and Zhang et al. (2014), temperature and relative humidity are primary and critical monitoring parameters to ensure the quality and safety of table grapes in cold chain. The temperature, which is one of the critical factors that directly affects the best storage environment conditions, is very important to prolong the table grapes storage life (Wang et al., 2017). The another critical parameter, relative humidity, will reduce the table grapes quality if the relative humidity is higher and lower than that in the best storage environment conditions in the table grapes cold chain (Kim et al., 2015). However, the table grapes cold chain system is always complicated and changeable (Ngcobo et al., 2012) and it still exists the challenging issue for the long run operation of WSN in non-stop table grapes cold chain monitoring (Kuila and Jana, 2014), because the WSN is constrained by a large number of spatially distributed sensor nodes with limited energy and memory size (Chen and Wassell, 2012), low computational capability (Kumar 2014) and constrained communication bandwidth (Hoang et al., 2014). The energy efficiency of the WSN, which is constrained by the limited resource, is urgent to be improved and applied for increasing the transparency, traceability and stabilization in cold chain.

Data transmission mode of the WSN is one of the effective ways to synthetically balance the limited resource (Sudha et al., 2011). There are three kinds of the data transmission modes that applied widely in non-stop cold chain monitoring. They are transparency transmission mode, storage transmission mode and compression

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transmission mode. The transparency transmission mode directly aggregates and transmits the sensor data in aggregation node of WSN every sample interval. The storage transmission mode aggregates and stores the sensor data in aggregation node of WSN every sample interval, and transmits the stored data every data sending interval. For example, Jiang et al. (2009) aggregated and transmitted the water temperature and pH value under the transparency transmission mode of the WSN, and Ren et al. (2013) stored and transmitted the distributed data under the storage transmission mode of the unattended WSN. Both of the transparency transmission mode and the storage transmission mode have a large amount of data been transmitted in WSN and the storage transmission mode needs more memory size of the WSN for data storage (Ehsan and Hamdaoui, 2012). However, the transmission of the large amount of data increases the communication bandwidth workload (Pantazis et al., 2013) and the energy consumptions in WSN (Khan et al., 2015).

Compression transmission mode aggregates and compresses the sensor data in aggregation node of WSN every sample interval, and transmits the compressed data every data sending interval. Various data compression transmission mode and algorithms for WSN have been reported. For example, Larios et al. (2012) and Pinto et al. (2014) presented the data fusion algorithm to fuse the data and optimize energy consumption of WSN. Barcelo-Llado et al. (2012) proposed a practical distributed source coding scheme to increase the compression rate and the symbol error rate in large WSN. Villas et al. (2013) indicated the in-network compression method to reduce the size and number of exchanged messages by compressing the redundant data in WSN. Liu et al. (2014a, 2014b) integrated the quality-of-information with an information fusion method to control the duty cycles of the sensor nodes in WSN. Sheng et al. (2015) demonstrated a decode-and-forward cooperative transmission mode to optimize the sensor nodes. However, these conventional compression techniques need much higher computation ability and extra communication overheads in the WSN (Li et al., 2013a), and most of them must be sampled at the Nyquist theorem to represent the original sensor data without error (Brunelli and Caione, 2015).

Compressed sensing (CS), which is conducive to the data storage, data transmission and data processing (Haupt et al., 2008), provides an easy way for the data reconstruction without the constraint of the Nyquist theorem (Tsaig and Donoho, 2006; Candes and Wakin, 2008). The CS applications in WSN have also been studied. For example, Li et al. (2013b) presented an efficient communication scheme in WSN based on CS for data gathering. Caione et al. (2014) investigated the signal ensembles optimization method in WSN by using the CS. Quer et al. (2012) addressed the application of the CS for the online recovery of large data sets in WSN. The applications of the CS in WSN have provided the basis for the further more applications in actual conditions. The CS transmission mode, which is the compression transmission mode integrated with the CS, aggregates and samples the sensor data every sample interval in aggregation node of WSN, and transmits the sampled data every data sending interval. The sensor data could be simply compressed with less computation ability and communication overheads and accurately reconstructed with relatively few sampling amount in WSN (Xiao et al., 2016).

Described as the above discussion, the main objective of this study is to propose an energy-efficient sensing method for the cold chain management of table grapes. The energy-efficient sensing in non-stop cold chain monitoring was realized by combining the WSN and the CS transmission mode for the sensor data acquisition and transmission. The cold chain environmental performance, the CS performance, the energy consumption of WSN devices, the transmission efficiency and economic performance were comprehensively evaluated in actual cold chain of table grapes. The proposed energy-efficient sensing method could reduce the average energy consumption of WSN devices and improve the operation and transmission efficiency of WSN, and finally increases the transparency, traceability and stabilization in cold chain.

The remainder of the paper is organized as follows. The energy-efficient sensing materials and methods are discussed in Section 2. The performance evaluation results of the energy-efficient sensing method are defined in Section 3. Conclusions and future work are presented in Section 4.

2. Materials and methods

This section presents in more detailed about the materials and methods for the research, which includes the properties of the table grapes cold chain investigated, the compressed sensing model for the sensor data acquisition and transmission, the implementation of the WSN nodes, and the experimental scheme for the actual cold chain evaluation.

2.1. Properties of the table grapes cold chain investigated

To identify the properties of the table grapes cold chain, a field observation and investigation for table grapes in cold chain was conducted from Xingjiang Uyghur autonomous region to Guangzhou city in China in 2015. The one-way cold chain transportation distance is about 4300 km, took about 15 d. The purpose is to understand the actual cold chain process and the transmission efficiency of WSN that may have influences on the safety and quality of table grapes. The workflow diagram and the actual cold chain process are illustrated and analyzed in more detailed in Fig. 1 and Table 1.

As described in Fig. 1 and Table 1, table grapes were picked and packed at the farm, and then transported to the cold storage for pre-cooling and storage by the ordinary transportation and to the markets for retail by refrigeration transportation. The ambient environment, such as the ambient temperature and ambient relative humidity, decreased the quality of table grapes quickly when they were in the process of picking, packing, ordinary transportation, loading, unloading and retail, and the stable refrigeration temperature and relative humidity prolonged the quality when they were in the process of pre-cooling, storage, and refrigeration transportation.

The stability of refrigeration temperature and relative humidity in cold chain, which is the critical factor to guarantee the table grapes quality and safety, was affected by the wireless communication load, the transmission time, the energy consumption, and the transmission efficiency of the WSN. The stability of refrigeration temperature and relative humidity would be decreased as the wireless communication load, the energy consumption and the transmission time of the WSN increased, and the transmission efficiency of the WSN decreased. However, it would also need more temperature and relative humidity sensors, which increases the wireless communication load, to accurately monitor the refrigeration temperature and relative humidity by the WSN if the refrigeration environment needs to be more stable.

The transmission time and energy consumption of the WSN are all increased once the wireless communication load is also increased. However, the energy consumption of the WSN would be increased as the transmission time increased at the same time because of the more operations needed in the WSN (Bonvoisin et al., 2012).

The transmission efficiency of the WSN, which is decreased as the wireless communication load, the energy consumption and transmission time of the WSN increased, could also prolong the