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Dynamic clustering and management of mobile wireless sensor networks

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ABSTRACT

In Wireless Sensor Networks (WSNs), routing data towards the sink leads to unbalanced energy consumption among intermediate nodes resulting in high data loss rate. The use of multiple Mobile Data Collectors (MDCs) has been proposed in the literature to mitigate such problems. MDCs help to achieve uniform energy-consumption across the network, fill coverage gaps, and reduce end-to-end communication delays, amongst others. However, mechanisms to support MDCs such as location advertisement and route maintenance introduce significant overhead in terms of energy consumption and packet delays. In this paper, we propose a self-organizing and adaptive Dynamic Clustering (DCMDC) solution to maintain MDC-relay networks. This solution is based on dividing the network into well-delimited clusters called Service Zones (SZs). Localizing mobility management traffic to a SZ reduces signaling overhead, route setup delay and bandwidth utilization. Network clustering also helps to achieve scalability and load balancing. Smaller network clusters make buffer overflows and energy depletion less of a problem. These performance gains are expected to support achieving higher information completeness and availability as well as maximizing the network lifetime. Moreover, maintaining continuous connectivity between the MDC and sensor nodes increases information availability and validity. Performance experiments show that DCMDC outperforms its rival in the literature. Besides the improved quality of information, the proposed approach improves the packet delivery ratio by up to 10%, end-to-end delay by up to 15%, energy consumption by up to 53%, energy balancing by up to 51%, and prolongs the network lifetime by up to 53%.

1. Introduction

In the last two decades, Wireless Sensor Networks (WSNs) have significantly changed the way we interact with our environment. WSNs appear in several scientific, commercial, health, surveillance, and military applications. Unattended sensor nodes offer maintenance-free operation and can detect, characterize and disseminate situational awareness continuously. After years of research on the opportunities provided by WSNs and their potential value, many of those looking to operate in the WSN market are starting to consider the potential practical problems, including data management. Once a WSN is up and running at full scale, it will generate large quantities of data that need to be processed and analyzed in real time.

The success of WSN applications is dependent on knowing that information is available, the type of information, its quality, its scope of applicability, limits of use, duration of applicability, likely return, cost to obtain and a host of other essential details. To aid in data collection, the use of mobile nodes has been widely suggested in the literature. Node movement can be controlled and optimized to improve data collection and analysis. For instance, mobile nodes can be used to bridge disconnected parts of the network. Furthermore, node mobility can optimize the energy consumption and lifetime of a WSN. For example, moving the sink to data sources or moving the sensor nodes towards the sink is one way to avoid the communication bottlenecks. However, the deployment of mobile nodes instigates frequent topological changes that need to be resolved before data collection can be resumed.

In this paper, we propose a holistic self-organizing mechanism that is based on [1]. The proposed mechanism is based on

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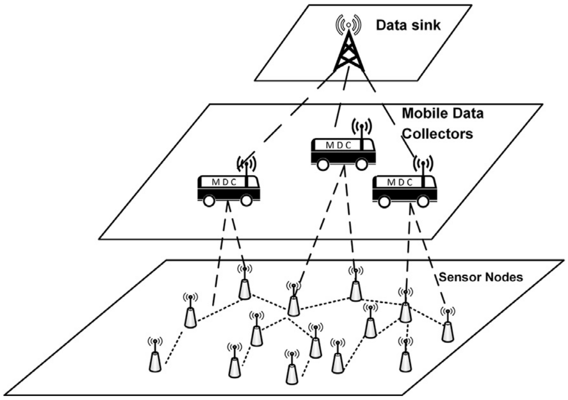

Fig. 1. A Three-tier network structure.

clustering the network in cooperating zones. This is achieved by abstracting the network to a three-tier pyramid model as shown in Fig. 1. Each tier contains a different class of sensor nodes. The bottom tier hosts static nodes, which form the majority of the network population. Sensor nodes at this tier perform sensing and communication tasks. The middle tier hosts a small number of resource-rich mobile nodes, called Mobile Data Collectors (for short, MDCs). MDCs have long-range radio and are considered power rich devices. The top tier of the hierarchy hosts the fixed data sink(s). At this tier, information received from different sources is processed and presented to end users.

It is desirable to design a distributed and self-organizing strategy featuring adaptability to network topology changes to reduce the cost of topology updates. Higher energy efficiency can be achieved by reducing the frequency of connectivity disconnections. Fewer and shorter disconnections results in reduced signaling overhead and lower packet loss.

The mobility management protocol proposed in this paper assumes that nodes have knowledge of their physical location. Nodes can determine their location in several ways. The Global Positioning System (GPS) is the simplest localization method. GPS modules are known for their high energy consumption. They also increase the total cost of each sensor nodes. Currently, the CRIUS MultiWii MWC I2C-GPS module costs less than $5. GPS-based solutions can become very expensive in large-scale WSN deployments. Therefore, several localization algorithms that do not relay on GPS modules have been introduced in the literature, e.g., [2,3]. Localization algorithms use various information available from the network in order to calculate the correct position of each sensor node. There are several localization techniques for indoor and outdoor environments described in the literature [4–6]. The use of localization algorithms introduces additional challenges that need to be addressed, including: (1) Localization latency: the localization algorithm should take minimal time to cope with mobility speed; (2) Increased control messaging: managing nodes location information requires communications and transmission of control packets. In mobile WSN where nodes change their location frequently, the localization control overhead will increase significantly causing network congestion and leading to higher energy consumption. In the proposed system, we assume that all MDCs and a small percentage of nodes are equipped with GPS modules. Other nodes in the network can estimate their location by using a centroid formula, where anchor nodes transmit their location to the blind nodes. This method keeps the system cost low, while maintaining low localization overhead [2,3,5].

The remainder of this paper is organized as follows: Section 2 examines background and related work in the area of MDCs in WSNs. Section 3 briefly introduce each phase of the proposed dynamic clustering technique, DCMDC. Section 4 presents the details DCMDC processes and phases. Section 5 discusses how DCMDC handles orphaned nodes. Section 6 presents the evaluation results of DCMDC and compares them against two of its best rivals in the literature. Section 7 concludes the paper.

2. Related work

Network clustering has been widely investigated by the WSN research community in the past two decades. In such clustering schemes, sensor nodes are divided into multiple logical groups according to some rules. These rules may be relate to a node's deployment, capabilities or other network dynamics [7]. The literature is very rich with effective clustering approaches designed for WSNs. The work in [8] focused on preserving complete coverage of the monitored area over long periods. The authors in [9] proposed a cluster based algorithm for tracking a mobile target to achieve high tracking accuracy and energy efficiency. Other propositions exist in the literature devoted to study mobility estimation and mobility supporting protocols in WSNs; a recent schedule-based MAC protocol for static and mobile nodes is investigated in [10].

Several hierarchical architectures have been considered for various applications of mobile WSNs [7,11–15]. In some approaches, cluster heads are used as MDCs besides their sensing duties. MDCs are used to carry information from the sensing field and deliver it to a fixed sink. In these approaches, sensor nodes send data over short-range communication, from a sensor to the MDC, which requires less transmission power due to the reduced bridging distance between data sources and the sink. MDCs also avoid the effect of bottlenecks, especially in areas around the sink, such as packet loss, increased end-to-end delay and energy depletion. The existence of multiple data collectors reduces the breakdown of interconnections; meaning that if one data collector fails, data can be transmitted through another data collector.

Although using MDCs is desirable due to their simplicity and efficiency, they introduce major challenges. Managing MDC location information requires communication and transmission of control packets. When the location changes frequently, the control packet overhead will increase, which leads to higher energy consumption. This may possibly dissipate the energy gains achieved by the MDCs. Moreover, the movement of MDCs may introduce significant data delivery delay caused by link establishment time, velocity control, etc. Finally, the MDC travel trajectory calculation is a complex problem.

There are several approaches devoted to the study of hierarchical mobile WSNs. Energy efficient routing protocols for multiple MDCs are investigated in [16,17]. The placement and relocation of multiple MDCs is investigated in [18]. Data collection approach to support mobility with multiple MDCs is presented in [19]. Secure cluster head election, where the cluster head is not a malicious node, is presented in [20]. However, there is only a handful set of papers directly addressing the problem of relay nodes mobility management.

In [21], the author proposed an Energy-efficient Cluster-based Data Gathering Algorithm (ECDGA) for mobile WSNs. The network model of ECDGA consists of heterogeneous sensor nodes. Static nodes are deployed in a grid to manage dynamic changes in the topology and relay sensed data from nearby cluster heads to a slow-moving sink. The cluster head selection is based on the residual energy and location of the mobile nodes. The authors show that ECDGA effectively prolongs the network lifetime. Nonetheless, ECDGA algorithm does not consider mobility parameters such as mobility speed and direction when allocating mobile nodes to clusters.