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### Mobile coordinated wireless sensor network

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**Abstract**—This paper introduces the mobile access coordinated wireless sensor network (MC-WSN) — a novel energy efficient scheme for time-sensitive applications. In conventional sensor networks with mobile access points (SENMA), the mobile access points (MAs) traverse the network to collect information directly from individual sensors. While simplifying the routing process, a major limitation with SENMA is that data transmission is limited by the physical speed of the MAs and their trajectory length, resulting in low throughput and large delay. In an effort to resolve this problem, we introduce the MC-WSN architecture, for which a major feature is that: through active network deployment and topology design, the number of hops from any sensor to the MA can be limited to a pre-specified number. In this paper, we investigate the optimal topology design that minimizes the average number of hops from sensor to MA, and provide the throughput analysis under both single-path and multipath routing cases. Moreover, putting MC-WSN in the bigger picture of network design and development, we provide a unified framework for wireless network modeling and characterization. Under this general framework, it can be seen that MC-WSN reflects the integration of structure-ensured reliability/efficiency and ad-hoc enabled flexibility.

**Index Terms**—Wireless sensor networks, mobile access coordinator, N-hop network, throughput, energy efficiency.

#### INTRODUCTION

Wireless sensor network (WSN) has been identified as a key technology in green communications, due to its indispensable role in both civilian and military applications, such as reconnaissance, surveillance, environmental monitoring, emergency response, smart transportation, and target tracking. Along with recent advances in remote control technologies, Unmanned Aerial Vehicles (UAVs) have been

utilized in wireless sensor networks for data collection [1], [2], as well as for sensor management and network coordination. Network deployment through UAV has also been explored in literature [3], [4].

For efficient and reliable communication over large-scale networks, sensor network with mobile access points (SENMA) was proposed in [1]. In SENMA, the mobile access points (MAs) traverse the network to collect the sensing information directly from the sensor nodes. SENMA has been considered for military applications, where small low-altitude unmanned aerial vehicles (UAVs) serve as the mobile access points that collect sensing information for surveillance, reconnaissance and collaborative spectrum sensing [5]. When the energy consumption at the MAs is not of a concern, SENMA improves the energy efficiency of the individual sensor nodes over ad-hoc networks by relieving sensors from complex and energy-consuming routing functions. While simplifying the routing process, a major limitation with SENMA is that a transmission is made only if an MA visits the corresponding source node; thus, data transmission is largely limited by the physical speed of the MAs and the length of their trajectory, resulting in low throughput and large delay.

In addition to SENMA, ad hoc networks with mobile sinks have also been explored by other researchers. In [2], a mobile sink is utilized for data collection, where it visits a limited number of pre-defined collection points in the network. Each sensor routes its information to the nearest collection point through multi-hop routing, then data is delivered to the sink when it visits the corresponding location. Similar approach has been considered in [6]. As in the case of the

conventional SENMA, the main limitation of these approaches is that data transmission depends on the physical speed of the access point, which is not desirable for time-sensitive applications.

In [7], a different network set-up with a mobile sink is presented. In this approach, certain nodes along a ring in the network are informed about the location of the sink. For data transmission, a node first acquires the sink's location, then forwards the packet to an anchor node which is closest to the current sink location. If the sink moves to a new location, the old anchor node will be updated with the new anchor node that is closest to the sink. One limitation of this approach is the overhead associated with the sink location acquisition, which would impact the throughput and delay of data transmission as well as the energy efficiency due to the frequent transmission and reception of control messages. In [8], mobile relays are utilized to facilitate data collection. However, this would be inefficient in terms of energy consumption as well as delay.

In this paper, by exploiting the most recent advances in Unmanned Aerial Vehicles (UAVs) and wireless charging [3], [4], we propose a mobile access coordinated wireless sensor network (MC-WSN) for time-sensitive, reliable, and energy-efficient information exchange. In MC-WSN, the whole network is divided into cells, each is covered by one MA, and served with powerful center cluster head (CCH) located in the middle of the cell, and multiple ring cluster heads (RCHs) uniformly distributed along a ring within the cell. The MAs coordinate the network through deploying, replacing and recharging the nodes. They are also responsible for enhancing the network security, by detecting compromised nodes then replacing them. Data transmission from sensor nodes to the MA goes through simple routing with cluster heads (CHs), CCH or RCHs serving as relay nodes. As in SENMA, the sensors are not involved in the routing process. A major feature of MC-WSN is that: Through active network deployment and topology design, the number of hops from any sensor to the MA can be limited to a pre-specified number. As will be shown, the hop number control, in turn, results in better system performance in throughput, delay, energy efficiency, and security management.

We would like to point out that this is an extension to our previous work in [9], [10], where we presented a simplified MC-WSN with a single RCH and multiple RCHs, respectively. In this paper, first, we discuss optimal topology design for MC-WSN such that the average number of hops between the source and its nearest sink is minimized; second, we analyze the throughput of MC-WSN under both single-path and multipath routing cases; and finally, we provide a more fundamental reasoning for the design of MC-WSN from the network evolution perspective, and characterize the convergence of centralized and ad hoc networking using a unified framework.

As an important measure of network performance, throughput is generally defined as the amount of information that can be successfully transmitted over a network, and is largely determined by the network model and transmission protocols. Existing work on throughput analysis is versatile [11]–[17], including one-hop centralized cases [11], [12] and ad-hoc cases [13]–[15]. There was also research on systems with mobile nodes [18], [19] and systems with mobile access points, like SENMA [1].

In [13], the throughput of random ad-hoc networks is studied. It was shown that the throughput obtained by each node vanishes as the number of nodes in the network increases. More specifically, for an ad-hoc network containing  $n$  nodes, the obtainable throughput by each node is  $O(\frac{1}{\sqrt{n}})$  bit-meters/sec, the maximum capacity of each link in the network. Note that the size or density of an ad-hoc network or a wireless sensor network plays a critical role in the network performance. This result indicates that for reliable and efficient communications, the network cannot be completely structure-less, but should have a well-defined structure while maintaining sufficient flexibility. This thought has actually been reflected in the merging of centralized and ad-hoc networks, leading to ad-hoc networks with structures, known as hybrid networks [20], [21]. As will be shown in Section II, the proposed MC-WSN is also an example of hybrid network: it has a hierarchical structure supported by the CCH, RCHs, and CHs; at the same time, it also allows partially ad-hoc routing for network flexibility and diversity.

In sensor networks with mobile sinks, as SENMA, since there is a direct link between each

sensor and the mobile sink, the system throughput is significantly superior to that of ad-hoc sensor networks [1]. However, a sensor can only transmit when an access point is within the sensor's communication range [1]. Hence, the throughput is limited by the access point's traversal speed and its trajectory length.

In this paper, we analyze the throughput of MC-WSN under both single path and multi-path routing. We evaluate the average per node throughput and compare it with that of SENMA. It is observed that the throughput of MC-WSN is independent of the physical speed of the MA, and hence is orders of magnitude higher than that of the conventional SENMA.

We propose a reliable and efficient mobile access coordinated WSN (MC-WSN) architecture for time-sensitive information exchange. The MAs coordinate the network through node deployment, replacement, recharging, malicious node detection, and data collection. The energy efficiency for individual sensors is maximized as they are not involved in the routing process, and do not need to receive beacon signals from the MA. Through active network deployment, the number of hops from any sensor to its corresponding MA can be limited to a pre-specified number. The hop number control ensures efficient system performance, and also makes the quantitative characterization of MC-WSN (in terms of throughput, stability, and delay) more tractable. We present an optimal topology design for MC-WSN such that the average number of hops between a sensor and its nearest sink is minimized, and show that the number of hops from any sensor to the MA can be limited to a pre-specified number.

We calculate the throughput of MC-WSN considering both single path and multi-path routing between each source and its corresponding sink. More specifically: (i) we analyze the throughput from an information theoretic perspective, and show that as the packet length gets large, the throughput approximately equals to the average normalized information that passes through the channel between a source and its sink; (ii) we illustrate the effect of the number of hops on the throughput, and show that the throughput diminishes exponentially as the number of hops increases; (iii) we show that the throughput of MC-WSN is independent of the physical speed of the

MA and the length of its trajectory, and is orders of magnitude higher than that of SENMA.

We provide energy efficiency analysis based on the radio energy dissipation modeling. We show that MC-WSN has significantly higher energy efficiency than the conventional SENMA. We discuss the design of MC-WSN in the bigger picture of network design and development. First, we revisit the convergence of centralized and ad-hoc networks, and discuss the general network design criteria from the network evolution perspective. Second, we provide a unified framework – the N-hop network. It includes all the existing networks as special cases. Using the MC-WSN as an example, we show that the N-hop framework can help regulate the design and systematic performance analysis of wireless networks, and provide an analytical tool to characterize the convergence of centralized and ad-hoc networks.

Our analysis is demonstrated through numerical results. It is shown that MC-WSN achieves much higher throughput and energy efficiency than SENMA. Overall, the hierarchical and heterogeneous structure makes MC-WSN a highly resilient, reliable, and scalable architecture. Moreover, the methods used here for network design and analysis provide insight for more general network modeling and evaluation.

## THE PROPOSED MOBILE ACCESS COORDINATED

### WIRELESS SENSOR NETWORK (MC-WSN)

In this section, we describe the proposed MC-WSN architecture and highlight its major features.

#### *A. General Description*

We assume the network is divided into cells of radius  $d$ . Each cell contains a single powerful mobile access point (MA) and  $n$  uniformly deployed sensor nodes (SNs) that are arranged into  $NCH$  clusters. Each cluster is managed by a cluster head (CH), to which all the cluster members report their data. CHs then route the data to the MA [9], [10], [22]. A powerful center cluster head (CCH) is employed in the middle of each cell, and  $K$  powerful ring cluster heads (RCH) are placed on a ring of radius  $R_t$ . The

CCH and RCHs can establish direct communication with the MA or with other RCHs that are closer to the MA. All nodes within a distance  $R_o$  from the CCH route their data to the MA through the CCH. All other nodes route their data to the MA through the nearest RCH. If a sensor is within the MA's coverage range, then direct communications can take place when permitted or needed. After receiving the data of the sensors, the MA delivers it to a Base Station (BS). The overall network architecture is illustrated in Figure 1. As will be illustrated in Section III, the number of hops from any sensor to the MA can be limited to a pre-specified number through the deployment of CCH and RCHs.

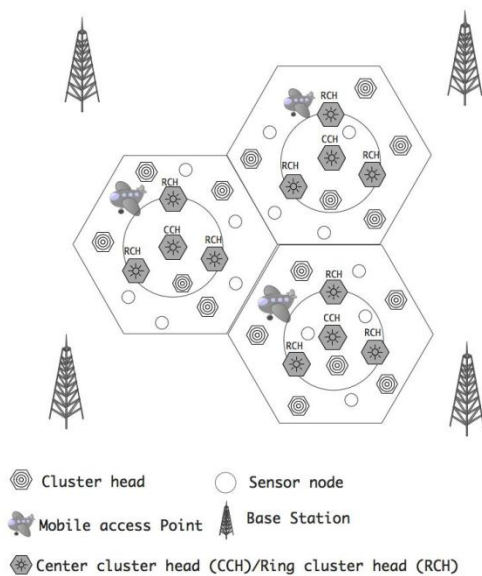


Fig. 1. Proposed MC-WSN architecture

In the proposed MC-WSN architecture, the MA coordinates the sensors and resolves the node deployment issue as well as the energy consumption problem of wireless sensor networks. More specifically, the MAs are responsible for: (i) deploying nodes, (ii) replacing and recharging nodes, (iii) detecting malicious sensors, then removing and replacing them, (iv) collecting the information from sensors and delivering it to a BS.

When an MA needs to be recharged or reloaded, it sends a request to the MA base. The base will send a new MA to the cell, and the substituted MA will be called back to the base for maintenance services. The MAs can move on the ground, and can also fly at low altitude. Each MA traverses its cell mainly for replacing or recharging

low-energy sensor nodes and cluster heads, as well as removing the malicious nodes. The recharging can be performed in a wireless manner [23]. The MA moves physically for data collection only in the case when the routing paths do not work.

Data collection from the sensors can be event based or periodic. Data transmissions from SNs to CHs, between CHs, and from CCH/RCHs to the MA are made over different channels to avoid interference between different communication links. Let the communication range of each sensor node and CH be  $r_c$  and  $R_c$ , respectively. CHs have larger storage capacity and longer communication range than SNs, i.e.,  $R_c > r_c$ . We assume shortest path routing between the CHs and the CCH/RCHs. Note that the sensors are not involved in the inter-cluster routing in order to minimize their energy consumption.

Due to the MA-assisted active network deployment, we can assume that the nodes are uniformly distributed in the network. It is therefore reasonable to place the powerful RCHs at evenly spaced locations on the ring  $R_t$ . To maximize the throughput and minimize the delay of data transmission from the sensors to the MA, the number of hops needed in routing should be minimized. In Section III, we discuss network topology design and obtain the optimal  $R_t$  and  $R_o$  that minimize the number of hops.

Discussions on Feasibility: (i) In general, topology control is difficult for large scale networks, especially under non-ideal topographical conditions. In the proposed work, this problem is significantly simplified. A main advantage of the proposed mobile coordinated WSN is that we exploit the recent advances in UAVs. Here each mobile access (MA) is an advanced UAV which can de-ploy, replace and recharge the nodes. For large network deployment, as in cellular networks, the whole area is divided into cells, and each cell is coordinated by one MA. On the other hand, in MC-WSN, ad-hoc routing is allowed between the cluster heads. However, hop number control is enforced to improve the throughput, delay and energy efficiency. For environments with obstacles, to ensure that the number of hops between the basic node and base station is within a pre-specified number, we need to deploy more RCHs, and even more base stations. As can be seen, with powerful mobile access

coordination, large-scale sensor network deployment under harsh environmental conditions becomes feasible and practical. (ii) It is true that even with the powerful mobile access, which is actually an advanced UAV, which can deploy, replace and recharge the nodes, uniform deployment may still be difficult to achieve due to geographic limitations such as slopes, obstacles, etc. In this case, to ensure that the number of hops between the basic node and base station is within a pre-specified number, we need to deploy more RCHs rather than being limited by the uniform requirement. The uniform deployment assumption made in the paper is used to make the theoretical analysis more tractable.

### B. Major Features

The main advantages of MC-WSN lie in: (i) multi-functionality of the mobile access; (ii) hop number control through topology design; and (iii) hierarchical and heterogeneous node deployment. More specifically, MC-WSN has the following features:

Controlled network deployment and prolonged net-work lifetime The proposed MC-WSN allows the MAs to manage the deployment of SNs and CHs. That is, the MA can add more nodes, relocate or replace exiting nodes. In addition, it can recharge or replace low-energy nodes. When a node has low remaining energy, it sends a control message to the MA notifying it with its energy level. The MA can then check and make the decision to replace the node or recharge it. Being coordinated by the MA, the MC-WSN architecture resolves the network deployment issue and can actively prolong the network lifetime.

- Time-Sensitive Data Transmission

In conventional SENMA, a transmission is made only if an MA visits the corresponding source node; thus, data transmission is limited by the physical speed of the MAs and the length of their trajectory, resulting in low throughput and large delay. In MC-WSN, the delay is effectively managed through hop number control, and is independent of the physical speed of the MA; in addition, unlike in [7], data transmission does not involve large amount of control messages for sink location acquisition.

- Enhanced network security

First, the MAs can detect malicious SNs and CHs and replace them [24]. When the MA receives data from a node, it first authenticates the source and checks its identity. If the source passes the authentication procedure, the MA detects malicious SNs and CHs and replaces them [24]. When the MA receives data from a node, it first authenticates the source and checks its identity. If the source passes the authentication procedure, the MA monitors the reports of each individual node and compares it with the final decision obtained through data fusion. Based on the observations over multiple sensing periods, the malicious nodes can be detected and removed [25].

## CONCLUSIONS

In this paper, a mobile access coordinated wireless sensor networks (MC-WSN) architecture was proposed for reliable, efficient, and time-sensitive information ex-change. MC-WSN exploits the MAs to coordinate the network through deploying, replacing, and recharging nodes, as well as detecting malicious nodes and replacing them. The hierarchical and heterogeneous structure makes the MC-WSN a highly resilient, reliable, and scalable architecture. We provided the optimal topology design for MC-WSN such that the average number of hops from any sensor to the MA is minimized. We analyzed the performance of MC-WSN in terms of throughput. It was shown that with active network deployment and hop number control, MC-WSN achieves much higher throughput and energy efficiency over the conventional SENMA. Our analysis also indicated that with hop number control, network analysis does become more tractable. Moreover, putting MC-WSN in the bigger picture of network design and development, we provided a unified framework for wireless network modeling and characterization. Under this general framework, it can be seen that MC-WSN reflects the integration of structure-ensured reliability/efficiency and ad-hoc enabled flexibility.

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