# Mobile Access Coordinated Wireless Sensor Networks – Topology Design and Throughput Analysis

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***Abstract*—In this paper, we propose a novel mobile access coordinated wireless sensor network (MC-WSN) architecture for reliable and efficient information exchange. 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 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 huge delay. The proposed MC-WSN architecture resolves this problem and provides an efficient solution for time-sensitive information exchange. In MC-WSN, the delay is effectively managed through hop number control. We analyze the throughput of the network, and show that the throughput of the MC-WSN is independent of the physical speed or the trajectory length of the mobile access point. The effectiveness of the proposed approach is demonstrated through simulations.**

***Index Terms*—Wireless sensor networks, mobile access coordinator, security and reliability, sensor network throughput.**

## I. Introduction

Wireless sensor networks (WSNs) were initially motivated by military surveillance applications. Recently, WSN has been identified as the key enabling technology for various civilian applications as well, such as environmental monitoring, emergency response, smart transportation, and target tracking. Along with the advancement in remote control technologies, Unmanned Aerial Vehicles (UAVs) have been utilized in wireless sensor networks for data collection [1], [2]. For efficient and reliable communication over large-scale networks, sensor networks 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. In general, low-altitude unmanned aerial vehicles (UAVs) serve as the mobile access points that collect sensing information for surveillance, reconnaissance and collaborative spectrum sensing [3]. 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 the energy-consuming routing functions.

While simplifying the routing process, a major limitation with SENMA is that a transmission is only made if the 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 huge delay. This makes SENMA undesirable for time-sensitive applications.

UAVs have also been used for management and coordination functions in wireless networks. For example, network deployment through UAV has been recently explored in literature [4], [5]. For sensor deployment, the UAV basically carries one or more sensor nodes, then flies to the required location and gets down to a specific altitude where it is safe to drop the sensor for deployment. A possible network deployment method using UAV was experimented in [5].

In this paper, mobile access coordinated wireless sensor network (MC-WSN) architecture is proposed 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 is served with powerful center cluster head (CCH) located at the middle of the cell, and multiple ring cluster heads (RCHs). The MAs coordinate the network through deploying, replacing and recharging 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 the CCH or the RCHs. 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. The hop number control, in turn, results in better system performance in delay, throughput, energy efficiency, and security management.

This paper extends our previous work in [6], where a single RCH is assumed. We analyze the throughput performance of the MC-WSN, and show that the throughput in MC-WSN depends on the number of data collectors, number of hops, per-hop distance, but is independent of the physical speed or the trajectory length of the MAs. We demonstrate the effectiveness of the proposed architecture through simulation examples, which show that the MC-WSN architecture achieves higher throughput over the conventional SENMA.

## II. The Proposed Mobile Access Coordinated Wireless Sensor Network (MC-WSN)

In this section, we describe the proposed MC-WSN architecture that aims at providing reliable, energy-efficient, and scalable network structure for prolonged-network lifetime and time-sensitive data exchange.

We assume the network is divided into cells each of radius $d$. Each cell contains a single powerful mobile access point (MA) and $n$ uniformly deployed sensor nodes (SNs) that are arranged into $K_{CH}$ 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. 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 RCH 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. 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 later, 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.

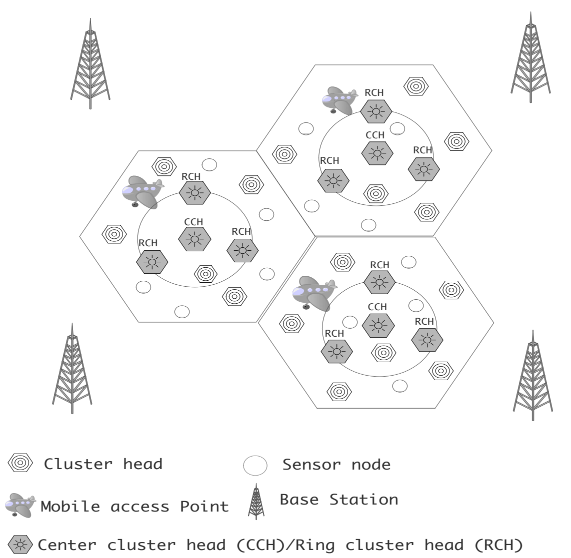


Fig. 1. Proposed MC-WSN architecture.

In the proposed MC-WSN architecture, the MA coordinates the sensor network 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 the 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 old MA will be taken back to the base for maintenance services. The MAs can move on the ground, and can also fly. Each MA traverses its cell mainly for removing the malicious nodes and replacing or recharging low-energy sensor nodes and cluster heads. It moves physically for data collection only in the case when the routing paths do not work.

Data transmission from any SN to the MA goes through simple routing, either with the CCH or the RCHs. Let the communication range of each sensor node and CH be $r_c$ and $R_c$, respectively. SNs only communicate with their corresponding CH, which then routes their data to the MA. CHs have larger storage capacity and longer communication range than SNs, i.e., $R_c > r_c$.

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

- *Resolving the network deployment problem and being able to actively prolong the network 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 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.
- *Being applicable for time-sensitive applications* In conventional SENMA architecture, data collection is limited by the physical velocity of the MA and the length of its trajectory; thus, the waiting time for an MA at a source node can be significantly large and would increase dramatically as the network size increases. Unlike in SENMA, the delay in MC-WSN is independent of the physical speed of the MA. In MC-WSN, the delay is effectively managed through hop number control.
- *Enhancing network security* The MAs can detect malicious SNs and CHs and replace them [7]. It is difficult to get the MA itself compromised or destroyed, since it is much more powerful than other network nodes, and it moves randomly in the network where its location can be kept private [8]. In addition, with hop number control, the delay from a sensor to the MA is limited within a pre-specified time duration under regular network conditions. If the actual delay is significantly larger, then an unexpected network event is detected.
- *Providing high energy efficiency* The SNs have the most limited resources in wireless sensor networks. In the proposed MC-WSN, SNs only communicate with their nearest CHs, and are not involved in any inter-cluster routing. Also, unlike SENMA, SNs in MC-WSN do not need to receive the beacon signal from the MA, and hence there is no energy consumed in receiving beacon signals.
- *Enhancing network resilience, reliability and scalability* MC-WSN is a self-healing architecture, where the CCH and RCHs represent different options for relaying the data to the MA. Each option can act as an alternative for the

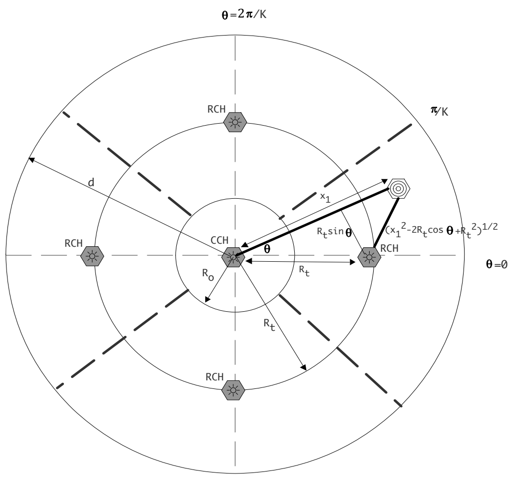


Fig. 2. MC-WSN with four powerful RCHs.

other. In the case when the routing paths do not work, the MA can traverse its cell for data collection. Overall, MC-WSN is a resilient, reliable and scalable architecture.

Due to the active network deployment feature in the proposed architecture, we can assume that the nodes are uniformly distributed in the network. It is also reasonable to place the powerful RCHs at evenly spaced locations on the ring $R_t$. Figure 2 shows an example of the MC-WSN with four RCHs.

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 IV, we design the topology and obtain the optimal $R_t$ and $R_o$ that minimize the number of hops.

## III. General network operations

In this section, we will briefly discuss the network set-up, sensing and collecting process, and malicious node detection operation.

### A. Network set-up

In the network set-up stage, the following procedures are followed: (i) Each sensor identifies its nearest CH, and communication channels are created between CHs and their cluster members (ii) Routes are established between each CH and the CCH or a RCH. (iii) Connections between the MA and the CCH/RCHs are set-up.

We assume shortest path routing between the CHs and the CCH/RCHs. The communications can be made over multiple hops through intermediate CHs acting as relays. Note that the sensors are not involved in the inter-cluster routing to minimize their energy consumption.

### B. Sensing and Data Collection

The sensing and collecting stage is performed periodically, where the individual sensors monitor the environment and report their information to the CHs. When TDMA is used within clusters, each SN reports to its corresponding CH a *data* message in its allotted time slot. CHs then forward the message to the CCH or the nearest RCH, which in turn routes the information to the MA. Data transmissions from SNs to CHs, between CHs, and from CCH/RCHs to the MA are made over different channels to avoid interference between the different communication links.

The MA sends a *beacon* signal frequently to the CCH and RCHs on a dedicated channel for synchronization purposes. If an MA visits an area for data collection, it sends a reference signal to the CHs within its coverage area over the channel(s) used by the corresponding clusters. The receiving CHs respond directly by sending their data to the MA. If the data is received correctly, the MA responds with an ACK.

### C. Malicious Node Detection

When the MA receives data from a node, it first authenticates the source and checks its identity. If the source passes the authentication procedure, its data would be used in the final decision making process. Some authenticated sensors may be compromised and report fictitious data. This is known as Byzantine attacks [7]. The MA should be able to detect these malicious nodes and avoid their harmful effects. One way to detect compromised nodes is to use a reliable distributed detection scheme [7], where data fusion is applied on the information collected from many sources to obtain the final decision. The MA monitors the reports of each individual node and compares it with the final decision obtained by the data fusion. Based on the observations over several sensing periods, the malicious nodes can be detected and removed. As the number of nodes involved in the data fusion procedure increases, the detection accuracy can be improved significantly, even if the percentage of malicious nodes is fixed [7].

## IV. Topology design

In this section, we obtain the optimal radius $R_o$ and the ring radius $R_t$ that minimize the required number of hops from any CH to the MA. The number of hops is proportional to the distance between the source and the sink. That is, to minimize the number of hops, *we design the topology such that the average distance between any cluster head and a sink is minimized*. In the proposed MC-WSN architecture, the average squared distance between any source and the corresponding sink (CCH/RCH) is expressed as:

$$\bar{d}^2 = 2K \Bigg[ \int_{\theta=0}^{\pi/K} \int_{x=0}^{R_o} x^2 f_X(x) f_\theta(\theta) dx d\theta + \int_{\theta=0}^{\pi/K} \int_{x=R_0}^{R_t} \left[x^2 - 2xR_t\cos(\theta) + R_t^2\right] f_X(x) f_\theta(\theta) dx d\theta + \int_{\theta=0}^{\pi/K} \int_{x=R_t}^{d} \left[x^2 - 2xR_t\cos(\theta) + R_t^2\right] f_X(x) f_\theta(\theta) dx d\theta \Bigg] \quad (1)$$

where $x$ is the distance from any CH to the center of the cell and $\theta$ is the angle from the CCH, as illustrated in Figure 2. $f_X(x)$ is the PDF of $x$; assuming that the CHs are uniformly distributed in a circle of radius $d$, it can be approximated by $f_X(x) = \frac{2x}{d^2}$, and the PDF of $\theta$ is $f_\theta(\theta) = \frac{1}{2\pi}$

We obtain the optimal $R_o$ by setting the derivative $\frac{\partial \bar{d}^2}{\partial R_o} = 0$; we get the optimal $R_o = \frac{\pi R_t}{2K \sin(\frac{\pi}{K})}$. Then, by substituting $\frac{\partial \bar{d}^2}{\partial R_t} = 0$, we get $R_t = \frac{\sqrt{3}-1}{\pi} K \sin(\frac{\pi}{K}) d = 0.233 K \sin(\frac{\pi}{K}) d$. It follows that $R_o = 0.366 d$. It is noted that $K$ must be greater than one. Therefore, we have the following result.

***Proposition 1****: To minimize the number of hops in the MC-WSN architecture with $K$ powerful RCHs, where $K > 1$, the following conditions should be met: (1) The CHs within a distance $R_o = 0.366\ d$ from the center of the cell deliver their data to the MA through the CCH. (2) Nodes at a distance $x$ from CCH, where $R_o \leq x < d$, deliver their data to the MA through the the nearest RCH on the ring of radius $R_t = 0.233 K \sin(\frac{\pi}{K}) d$.*

With the optimal topology, the average squared distance is $\bar{d}^2 = 0.5 d^2 - 0.047 d^2 K^2 [\sin(\frac{\pi}{K})]^2$. Assuming shortest path routing is available, the average number of hops can be expressed as $N_{hop} = \frac{\bar{d}}{R_c}$, where $R_c$ is the communication range of the cluster heads.

## V. Throughput Analysis

In this section, we analyze the per-node throughput of the multihop MC-WSN architecture.

Let $t_i^j$ be a binary flag indicating that node $i$ transmits data to sink $j$, i.e., $t_i^j = 1$ means that sensor $i$ is scheduled to transmit its data to the sink $j$, otherwise $t_i^j = 0$, where $j \in \{1, 2, ..., K+1\}$. Similarly, let $r_i^j$ be a binary flag indicating that the data of node $i$ is successfully received at the intended destination (CCH/RCH) $j$. Note that the transmission from the powerful CCH/RCH to the MA can be made at high-power and high-rate. Also, with the active network deployment performed by the MA, the data from each sensor to its CH can be made over a single hop using TDMA protocol. Thus, we focus on data transmission from the CH of the originating node to the CCH/RCH.

Define *the throughput of node* $i$, $T(i)$, as the average number of packets per slot that are initiated by node $i$ and successfully delivered to the intended receiver [9]. Define $R_S(t)$ as the set of nodes that have their packets successfully delivered in slot $t$ when $S$ is the set of nodes scheduled to transmit. Then, $T(i)$ can be expressed as:

$$\begin{aligned} T(i) &= E\left[\lim_{T\to\infty} \frac{1}{T} \sum_{t=1}^{T} I[i \in R_S(t)]\right] \\ &= \lim_{T\to\infty} \frac{1}{T} \sum_{t=1}^{T} Pr\{i \in R_S(t)\}, \end{aligned} \tag{2}$$

where $I(.)$ is the indication function. Assume that the packet reception from slot to slot is an i.i.d process, then $T(i)$ will be equivalent to:

$$T(i) = Pr\{r_i^j = 1 | t_i^j = 1\} Pr\{t_i^j = 1\}. \tag{3}$$

The *network throughput*, $\Upsilon$, is defined as the average number of packets received successfully from all clusters per unit time. The network throughput can be expressed as:

$$\Upsilon = E\left[\lim_{T\to\infty} \frac{1}{T} \sum_{i=1}^{K_{CH}} \sum_{t=1}^{T} I[i \in R_S(t)]\right] = \sum_{i=1}^{K_{CH}} T(i). \tag{4}$$

In the following, we focus on the per-node throughput.

Consider that node $i$ requires $N_i^j$ hops to reach sink $j$. $N_i^j$ is based on the network architecture, topology, and routing scheme. Let the ideal or shortest path from node $i$ to the sink be $i_0 \to i_1 \to ... \to i_{N_i^j}$, where $i_0$ is the source node (CH) $i$ and $i_{N_i^j}$ is the sink. Let $t_{i,h}^j$ be a binary flag at hop $h$, indicating that node $i_{h-1}$ is scheduled to relay a packet of node $i$ to node $i_h$ along the route to sink $j$. Also, let $r_{i,h}^j$ be a binary flag indicating that the data of node $i$ is successfully received at node $i_h$ along the same route to sink $j$. We have,

$$Pr\{r_{i,h}^j = 1\} = Pr\{r_{i,h}^j = 1 | t_{i,h}^j = 1\} Pr\{t_{i,h}^j = 1\}. \tag{5}$$

In order to have the data correctly received by the sink, all intermediate hops should be successful. For the throughput calculations here, we do not consider retransmissions of packets. In the case when the amplify-and-forward protocol is adopted in the relaying process, we have:

$$T(i) = \prod_{h=1}^{N_i^j} Pr\{r_{i,h}^j = 1 | t_{i,h}^j = 1\} Pr\{t_{i,h}^j = 1\}. \tag{6}$$

Since a node transmits a packet to the sink when all the intermediate relays forward its packet, we have $Pr\{t_i^j = 1\} = \prod_{h=1}^{N_i^j} Pr\{t_{i,h}^j = 1\}$. Thus, we can write:

$$T(i) = Pr\{t_i^j = 1\} \prod_{h=1}^{N_i^j} Pr\{r_{i,h}^j = 1 | t_{i,h}^j = 1\}. \tag{7}$$

It is noted from equation (7) that the throughput depends on the employed PHY, MAC, routing protocols as well as the network environment. $t_i^j$ is related to the MAC protocol, while $r_i^j$ is related to the PHY protocol. The routing protocol determines the path and the number of hops from the source to the destination.

Denote $N_{intf}$ as the minimum separation between links for bandwidth reuse. That is, when a transmission is made by a CH, other nodes within a distance $N_{intf} R_c$ from the transmitting CH should remain silent or use another orthogonal channel. Let $n_j$ be the number of nodes connected to sink $j$. When TDMA is used, each node connected to sink $j$ can transmit with a uniform probability $P(t_i^j = 1) > \frac{1}{N_{intf} n_j}$ [10]. If hybrid TDMA/FDMA is used, and $N_{freq}$ denotes the number of frequencies available for the CHs transmissions, then $P(t_i^j = 1) > \frac{N_{freq}}{N_{intf} n_j}$.

We now evaluate the probability of successful reception. Let $P_i$ be the power of node $i$ that is exponentially distributed with mean $1/\mu_i$. Assume $\mu_i = \mu\ \forall i$. The successful reception can be viewed as a condition on the $SINR$. Suppose a transmission is made from $l_i$ to $l_k$, where $l_i$ and $l_k$ are the locations of the transmitting and receiving nodes, respectively, and $L_{i,k} = |l_i - l_k|$ is the distance between them. The signal to noise and interference ratio in the transmission from $i$ to $k$, $SINR_{i,k}$, can be expressed as $SINR_{i,k} = \frac{L_{i,k}^{-\beta} P_i}{N_o + \sum_{x \in X^i \neq i} L_{x,k}^{-\beta} P_x}$, where $N_o$ is the noise power, $X^i$ is the set of all radios transmitting on the same channel and in the same time slot, and $\beta$ is the path loss exponent, where $\beta \geq 2$ ($\beta = 2$ in free space environment). In structured networks, the assignment of channels and time slots can be managed to minimize the interference. In this case, the interference term becomes negligible, and we get $SINR_{i,k} = \frac{L_{i,k}^{-\beta} P_i}{N_o}$.

We can write

$$Pr\{r_{i,h}^j = 1 | t_{i,h}^j = 1\} = Pr\{SINR_{i_{h-1}, i_h} > \gamma\}, \quad (8)$$

where $\gamma$ defines the SINR threshold for successful transmission. Define $\lambda_{i,h} = \gamma N_o \left[L_{i_{h-1}, i_h}\right]^\beta$ as the minimum transmit power of node $i_{h-1}$ to guarantee the SINR threshold at hop $h$. We have,

$$\begin{aligned} Pr\{SINR_{i_{h-1}, i_h} > \gamma\} &= Pr\{P_{i_{h-1}} > \lambda_{i,h}\} \\ &= \int_{s=\lambda_{i,h}}^{\infty} \mu \exp\{-\mu s\}\, ds \\ &= \exp\left\{-\mu\gamma N_o \left[L_{i_{h-1}, i_h}\right]^\beta\right\}. \end{aligned} \quad (9)$$

Form (7), we get

$$\begin{aligned} T(i) &= Pr\{t_i^j = 1\} \prod_{h=1}^{N_i^j} \exp\left\{-\mu\gamma N_o \left[L_{i_{h-1}, i_h}\right]^\beta\right\} \\ &= Pr\{t_i^j = 1\} \exp\left\{-\mu\gamma N_o \sum_{h=1}^{N_i^j} \left[L_{i_{h-1}, i_h}\right]^\beta\right\}. \end{aligned} \quad (10)$$

***Proposition 2****: In the multihop MC-WSN network, assuming exponentially distributed transmit powers, the throughput of node $i$ that is connected to sink $j$ is:*

$$T(i) = p_i^j \exp\left\{-\kappa \sum_{h=1}^{N_i^j} \left[L_{i_{h-1}, i_h}\right]^\beta\right\}, \quad (11)$$

*where $N_i^j$ is the number of hops in node $i$'s transmission, $p_i^j = Pr\{t_i^j = 1\}$ is the probability that node $i$ and all the intermediate relaying nodes are scheduled to transmit the data of node $i$ to sink $j \in \{1, 2, ..., K+1\}$, $\beta$ is the path loss exponent of the channel, $L_{x,y}$ is the distance between nodes $x$ and $y$, and $\kappa = \mu\gamma N_o$ as in (10).*

Based on the analysis above, the total throughput of the proposed MC-WSN with $K$ RCHs and a CCH is obtained as:

$$\Upsilon = \sum_{j=1}^{K+1} \sum_{i=1}^{n_j} p_i^j \exp\left\{-\kappa \sum_{h=1}^{N_i^j} \left[L_{i_{h-1}^j, i_h^j}\right]^\beta\right\}, \quad (12)$$

where $n_j$ is the number of nodes connected to sink $j$. $N_i^j$, $p_i^j$, and $L_{x,y}$ are defined in Proposition 2.

Now we obtain overall average per-node throughput. Define $P_{A_j}$ as the probability that a cluster lies in the coverage area of sink $j$. We set $P(t_i^j = 1) = \frac{N_{freq}}{N_{intf} n_j}$, which is a conservative per-node transmission probability. Then, the overall average per-node transmission probability $\bar{P}_t$ can be expressed as:

$$\begin{aligned} \bar{P}_t &= \sum_j P_{A_j} \frac{N_{freq}}{N_{intf} n_j} = \sum_j P_{A_j} \frac{N_{freq}}{N_{intf} P_{A_j} N_{CH}} \\ &= (K+1) \frac{N_{freq}}{N_{intf} N_{CH}}. \end{aligned} \quad (13)$$

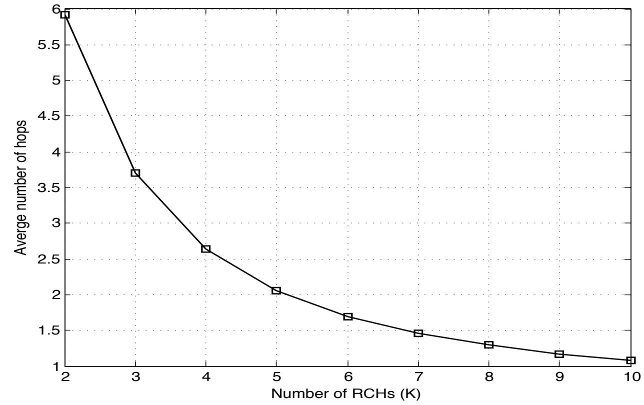


Fig. 3. Average number of hops versus the number of RCHs ($K$), when $d = 300$m and $R_c = 20$m.

For equidistant hops with length $R_c$, the overall average per-node throughput is expressed as $\bar{T} = \bar{P}_t \exp\{-\kappa N_{hop} R_c^\beta\}$, where $N_{hop}$ is the average number of hops.

*Discussions:* It can be seen from *Proposition 2* that if the hops are equidistant, and under the same channel conditions, the throughput will decrease as the number of hops increases. That is, when $L_{i_{h-1}, i_h} = L \; \forall h \in \{1, 2, .., N_i^j\}$, we get $T(i) \propto \exp\{-N_i^j\}$. It follows that $\lim_{N_i^j \to \infty} T(i) = 0$. That is why we limit the number of hops from each sensor to the MA to a pre-specified number, through the topology design and deployment of CCH and RCHs. With hop number control, we can have better control and management over the system's throughput, delay, security, and energy efficiency.

## VI. Simulation Results

In this section, we demonstrate the performance of MC-WSN through simulation examples. First, we show the effect of the number of RCHs on the average number of hops in data transmission. Then, we illustrate the delay and per-node throughput performance of the MC-WSN, and compare it to SENMA.

*Controlling the number of hops:* Figure 3 shows the average number of hops versus the number of RCHs ($K$). As expected, when $K$ increases, the average number of hops decreases. It is noted that in the case when only the CCH is employed, which corresponds to the traditional centralized networks, the average number of hops is $\frac{2d}{3R_c}$. Under the same settings used in Figure 3, it is clear that data transmission in MC-WSN can effectively be made through less number of hops as compared to traditional centralized network model with a single sink.

*Delay:* In MC-WSN, the delay in a packet delivery ($D_M$) can be roughly expressed as: $D_M = C_1 \frac{L_t}{V_{EM}}$ , where $C_1$ is a constant, $V_{EM} = 3 \times 10^8\ m/s$ is the electromagnetic wave (EM) propagation speed, and $L_t$ is the total distance traveled by the signal. Note that $L_t < d$. We can let $L_t = \alpha d$, where $\alpha < 1$. In SENMA, the SNs wait for the MA visit to report their data; hence, the delay depends on the velocity of the MA, as well as the cell size; that is, the delay for a node to report its data to the MA in SENMA is $D_S = C_2 \frac{d^2}{V_{MA}}$ [1], where $V_{MA}$ is the MA speed and $C_2$ is a constant. We have $\frac{D_S}{D_M} = Cd\frac{V_{EM}}{V_{MA}}$, where $C$ is a constant. This implies that the proposed MC-WSN architecture could result in several orders of magnitude lower delay over SENMA. Table I shows the delay ratio $\frac{D_S}{D_M}$ for different cell sizes.

TABLE I
DELAY COMPARISON WITH $V_{MA} = 30\ m/s$.

| Cell edge length (m): $d$ | 100 | 1000 |
|---|---|---|
| Delay ratio: $\frac{D_S}{D_M}$ | $\propto 10^9$ | $\propto 10^{10}$ |

$D_S$: Average delay in SENMA, $D_M$: Average delay in MC-WSN.

*Throughput:* We evaluate the overall average per-node throughput of the MC-WSN and compare it to that of SENMA. Define the density of the sensor nodes and the cluster heads as $\rho_{SN} = \frac{n}{\pi d^2}$ and $\rho_{CH} = \frac{K_{CH}}{\pi d^2}$, respectively. Here, we set $\rho_{SN} = 0.0283$ and $\rho_{CH} = 0.0014$. The communication range of the sensor nodes and cluster heads are assumed to be $r_c = 15$m and $R_c = 30$m, respectively. Let the transmitted power of the CHs be exponentially distributed with mean $1/\mu = 1$mW. In the simulations, we set $\beta = 2$ and $\gamma = -5$dB. We assume that the $SNR = \frac{1/\mu}{N_o} = 20$dB, and the bandwidth reuse measure is $N_{intf} = 2$. For SENMA, we set the MA speed to $V_{MA} = 30$m/s. Let the trajectory length of the MA be $L_{MA}$. Therefore, the transmission probability of any sensor is evaluated as: $P(t_{SENMA} = 1) = \frac{T_{slot}}{\frac{L_{MA}}{V_{MA}} + nT_{slot}}$, where $T_{slot}$ is the slot duration assigned to each node for transmission. We set $T_{slot} = 25.6$ms.

In Figure 4, the overall average per-node throughput of MC-WSN with $K = 6$ and SENMA architecture are plotted versus the network cell radius. It can be shown that the throughput of the MC-WSN architecture is superior to that of SENMA. The main reason is attributed to the dependency of the data transmission in SENMA on the physical speed of the MA and the length of its trajectory. We show the cases when $N_{Freq} = 1$ and 4 in Figure 4. It can be seen that as the number of orthogonal frequencies increases, the throughput of the MC-WSN architecture can be further improved.

## VII. Conclusions

We proposed a reliable and time-efficient architecture design for mobile access coordinated wireless sensor networks (MC-WSN) with multiple data collection points. In the proposed architecture, the network exploits the mobile access points to actively deploy nodes, perform data collection, detect malicious sensors, and enhance the network security. The MC-WSN provides an efficient framework for time-sensitive information exchange. It also resolves the network deployment problem and prolongs the network lifetime actively. In contrast to SENMA, data transmission in MC-WSN architecture is independent of the physical speed of the access point. In MC-WSN, the delay can be effectively managed through hop number control. We analyzed the throughput of the network, and it was observed that the proposed architecture can potentially increase the network throughput over the conventional SENMA system.

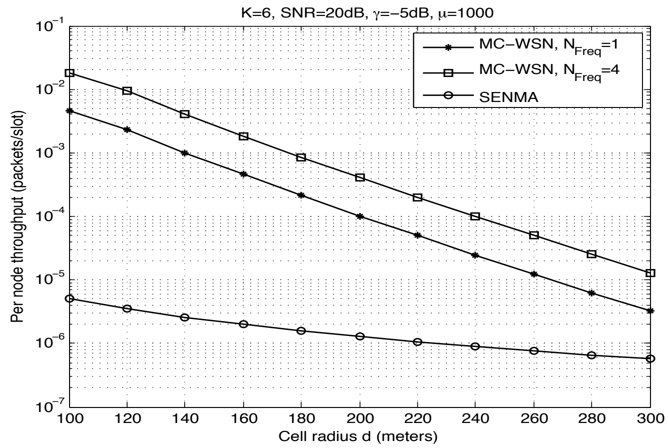


Fig. 4. Per-node throughput in packets per slot vs. the cell radius for MC-WSN and SENMA.


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