Mobile Coordinated Wireless Sensor Network: An Energy Efficient Scheme for Real-Time Transmissions

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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 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.

I. 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 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 multihop 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 $O(W/Vn)$ bit-meters/sec, where $W$ is 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 structureless, 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 multipath 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.

The major contributions of this paper can be summarized as follows:

- 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 multiplath 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 or 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 criterions 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.

II. 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 \( N_{CH} \) 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 [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.

![Proposed MC-WSN architecture.](image)

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 deploy, 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 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 existing 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 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]. In MC-WSN,
the access point traverses the network to replace low-power nodes or unreliable compromised nodes without affecting the normal data collection process in the network. Second, 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 or network failure is detected. Third, 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 [26].

- Efficient energy consumption 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 and similar approaches, SNs in MC-WSN do not need to receive the periodic beacon signal from the MA, and hence the energy efficiency is further improved. Note that the beacon signal in SENMA is used to notify the sensors of the presence of the MA and to indicate which sensor to transmit.

- Enhanced network resilience, reliability and scalability: MC-WSN is a self-healing architecture, where the CCH and RCHs represent different options for data transmission to the MA. The diversity in multipath routing increases the resilience of the network. In the worst case when the routing paths do not work, the MA can traverse its cell for data collection. Overall, the hierarchical and heterogeneous structure makes the MC-WSN a highly resilient, reliable, and scalable architecture.

III. NETWORK TOPOLOGY DESIGN

In this section, we investigate network topology design of MC-WSN, and calculate the optimal radius $R_o$ and the ring radius $R_t$ that minimize the average number of hops from any CH to the MA. As will be shown in the next section, minimizing the number of hops has a direct impact on maximizing the throughput. Since the basic sensor nodes are not involved in the routing process, the topology design is therefore focused on the multihop transmissions between CHs.

Note that under shortest path routing, the number of hops is proportional to the distance between the source and its corresponding sink. To minimize the number of hops, we design the topology such that the average distance between a cluster head and its nearest sink is minimized.

In the proposed MC-WSN architecture, the average squared distance between any source and the corresponding sink (CCH/RCH) can be expressed as:

$$d^2 = 2K \left[ \int_{\theta=0}^{\pi/K} \int_{x=0}^{R_o} x^2 f_X(x) f_\Theta(\theta) dxd\theta + \int_{\theta=0}^{\pi/K} \int_{x=R_o}^{R_t} \left[ x^2 - 2xR_t \cos(\theta) + R_t^2 \right] f_X(x) f_\Theta(\theta) dxd\theta \right] + \int_{\theta=0}^{\pi/K} \int_{x=R_t}^{d} \left[ x^2 - 2xR_t \cos(\theta) + R_t^2 \right] f_X(x) f_\Theta(\theta) dxd\theta,$$

where $X$ is the distance from the CH to the center of the cell, $\Theta$ is the angle of the CH in the polar system with CCH as the origin, as illustrated in Figure 2. $f_X(x)$ and $f_\Theta(\theta)$ denote the probability density function (PDF) of $X$ and $\Theta$, respectively. Here, we approximate the hexagonal cell deliver their data to the CCH. (2) The CHs at a distance $x$ from CCH, where $R_o \leq x < d$, deliver their data to the MA through the nearest RCH on the ring of radius $R_t = 0.233K \sin(\frac{x}{K})$.

With the optimal topology, the average squared distance from a CH to its nearest sink (CCH/RCH) is $\bar{d}^2 = 0.5d^2 - 0.047d^2 + 0.233K^2 \sin(\frac{x}{K})^2$. Assuming shortest path routing is available, with sufficient network diversity, the average number of hops can be estimated as $N_{hop} = \frac{\bar{d}}{R_c}$, where $R_c$ is the communication range of the cluster heads. Note that as $K$ increases, $\bar{d}$ and consequently $N_{hop}$ decrease.

Here, we mainly focused on the multihop routing from a CH to CCH/RCH. The maximum number of hops from any sensor to the MA can be expressed as

$$N = 2 + \max \left\{ \frac{1}{R_c} \sqrt{R_o^2 - 2R_oR_t \cos(\frac{x}{K}) + R_t^2}, \sqrt{d^2 - 2dR_t \cos(\frac{x}{K}) + R_t^2} \right\},$$

where the first term accounts for the number of hops...
IV. THROUGHPUT ANALYSIS

In this section, we analyze the throughput of the multihop MC-WSN architecture. After introducing the definition of the throughput in the single hop case, we analyze the multihop throughput under both single path and multipath routing.

A. Definition of the Throughput

We start with the single hop case. Assuming node \( i \) is transmitting to sink \( k \), where \( k \in \{0, 1, ..., K\} \). The throughput of node \( i \) to sink \( k \), \( T_{i,k} \), is defined as the average number of packets per slot that are initiated by node \( i \) and successfully delivered to the intended receiver \( k \) [27]. Define \( R_S^k(\nu) \) as the set of nodes that have their packets successfully delivered to sink \( k \) in slot \( \nu \), where \( S \) is the set of nodes scheduled to transmit. Then, \( T_{i,k} \) can be expressed as:

\[
T_{i,k} = E \left[ \lim_{V \to \infty} \frac{1}{V} \sum_{\nu=1}^{V} I[i \in R_S^k(\nu)] \right] = \lim_{V \to \infty} \frac{1}{V} \sum_{\nu=1}^{V} Pr\{i \in R_S^k(\nu)\},
\]

where \( I(\cdot) \) is the indication function.

Let \( t_i^k \) be a binary flag indicating that node \( i \) transmits data to sink \( k \): \( t_i^k = 1 \) means that sensor \( i \) is scheduled to transmit its data to the sink \( k \), otherwise \( t_i^k = 0 \). Similarly, let \( r_i^k \) be a binary flag indicating that the data of node \( i \) is successfully received at the intended destination \( k \) (CCH or RCH). 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 transmitted over a single hop using a collision-free MAC protocol. Thus, we focus on data transmission from the CH of the originating node to its corresponding CCH/RCH. Assume that the packet reception from slot to slot is an i.i.d process, then it follows that:

\[
T_{i,k} = Pr\{t_i^k = 1 \mid t_i^k = 1\} Pr\{r_i^k = 1\}.
\] (5)

In the following, we analyze \( T_{i,k} \) from the information theory perspective, by discussing the relationship between \( T_{i,k} \) and the mutual information between the packet transmitted from CH \( i \) and the packet received at sink \( k \).

For each slot, define \( X_i^k \) as the transmitted packet from CH \( i \) to sink \( k \), where \( X_i^k = 0 \) means that node \( i \) is not transmitting. Let \( X_i^k \) be the non-zero packets of \( X_i^k \), then \( X_i^k = t_i^k X_i^k \) [11]. Assume that sink \( k \) receives packets from multiple nodes in a collision-free manner. Define \( Y^k \) as the received vector at sink \( k \), where the \( i \)th element in \( Y^k \) is the received packet from CH \( i \). Let \( r^k \) be the vector whose \( i \)th element is \( r_i^k \). It has been shown in [11] that the mutual information between \( X_i^k \) and \( Y^k \) can be written as a function of the throughput of CH \( i \) to sink \( k \) \( (T_{i,k}) \) as follows:

\[
I(X_i^k, Y^k) = I(t_i^k, r^k) + H(X_i^k)T_{i,k},
\] (6)

where \( I(x, y) \) is the mutual information between \( x \) and \( y \), and \( H(x) \) is the entropy of \( x \). Let \( I_p^k = I(X_i^k, Y^k)/H(X_i^k) \), which is measured in number of packets per slot. In general, \( T_{i,k} \leq I_p^k \). Note that \( t_i^k \) is binary, i.e., \( H(t_i^k) \leq 1 \), which implies that \( I(t_i^k, r^k) \leq H(t_i^k) \leq 1 \). As a result, if the packet length gets large, i.e., \( H(X_i^k) \rightarrow \infty \), then we have \( T_{i,k} \approx I_p^k \).

From the information theory perspective, this shows that \( T_{i,k} \) is the average normalized information (measured in packets per slot) passed through the channel between CH \( i \) and sink \( k \).

B. Multihop Single Path Routing Case

In this subsection, we analyze the throughput of a node in the case when there is a pre-defined multihop single path from each CH to its corresponding sink.

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

$$Pr\{t^k_{i_h} = 1\} = Pr\{t^k_{i_h} = 1 | t^h_{i_h} = 1\} Pr\{t^h_{i_h} = 1\}.$$  \hfill (7)

Consider that a packet of CH $i$ is received at sink $k$ in slot $\nu$. This implies that there exists a scheduling slot vector $\nu = [\nu - \Delta \nu_{N_k-1}, ..., \nu - \Delta \nu_1, \nu]$, such that all nodes along the routing path from $i$ to the sink successfully transmit the packet of node $i$. More specifically, node $i_h$ is scheduled to transmit in slot $\nu - \Delta \nu_{h-1}$, where $\Delta \nu_x > \Delta \nu_y$, $\forall x > y$ and $\Delta \nu_0 = 0$. Along slot vector $\nu$, define the transmission flag of CH $i$ as $t^i_{\nu}(\nu)$, such that $t^i_{\nu}(\nu) = [1, ..., 1]$ when CH $i$ transmits a packet to sink $k$ and the transmission at the last hop (CH $i_1$) occurs in slot $\nu$. Note that if the relay at the last hop along the transmission path from $i$ to the sink transmits the packet of node $i$, then it implies that all intermediate hops were scheduled to transmit in prior slots. That is, we have

$$Pr\{t^k_{\nu}(\nu) = 1\} = Pr\{t^k_{\nu,1}(\nu) = 1, ..., t^k_{\nu,N_k}(\nu - \Delta \nu_{N_k-1}) = 1\}.$$  \hfill (8)

Omit the slot index, (8) can be simplified as: $Pr\{t^k_i = 1\} = Pr\{t^k_i = 1, ..., t^k_{i,N_k} = 1\}$.

For the throughput calculation here, we do not consider retransmissions of packets. Assuming that there exists a schedule such that the source CH and all its intermediate relays are assigned time slots to transmit/forward the source’s data, and assuming that the transmissions in all slots are i.i.d., then we can drop the slot index from the throughput expression. In the case when the amplify-and-forward protocol is adopted in the relaying process, which implies that $t^k_{i_h}$'s are independent at different hops, it follows from (5) and (7) that:

$$T_{i,k} = Pr\{t^k_{i,1} = 1, ..., t^k_{i,N_k} = 1\} \prod_{h=1}^{N_k} Pr\{t^h_{i,h} = 1 | t^h_{i_h} = 1\} = Pr\{t^k_i = 1\} \prod_{h=1}^{N_k} Pr\{t^h_{i,h} = 1 | t^h_{i_h} = 1\}.$$  \hfill (9)

Note that if decode-and-forward is employed at the intermediate CHs instead of the amplify-and-forward, then the errors in one hop can be corrected at another hop experiencing better channel conditions. This is at the expense of increased complexity and delay at all hops.

It is noted from equation (9) that the throughput depends on the employed PHY, MAC, routing protocols as well as the network environment. $t^k_i$ is related to the MAC protocol, while $t^k_{i_h}$ is related to the PHY protocol. The routing protocol determines the path and the number of hops from a source to its 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 of $N_{intf} R_c$ from the transmitting CH should remain silent or use another orthogonal channel. Let $n_k$ be the number of nodes connected to sink $k$. Following similar process as in [17], we have the following result.

**Lemma 1.** When TDMA is used, each node connected to sink $k$ can transmit with a probability $P(t^k_i = 1) \geq \frac{1}{N_{intf} \cdot n_k}$. If hybrid TDMA/FDMA is used, and $N_{FREQ}$ is the number of frequencies available for simultaneous CHs transmissions within the same interference region, then $P(t^k_i = 1) \geq \frac{N_{FREQ}}{N_{intf} \cdot n_k}$.

**Proof:** The proof is provided in Appendix A. \hfill ■

In the following, we illustrate the transmission probability bound in Lemma 1 through an example. Consider two paths connected to sink $k$, each has three hops as shown in Figure 3. Note that node 3 transmits three packets to the sink: its own packet as well as packets of nodes 1 and 2. Similarly, node 6 transmits three packets to the sink, which are packets of nodes 4, 5 and its own packet. Nodes 2 and 5 transmit two packets, while nodes 1 and 4 transmit one packet. Assuming $N_{intf} = 3$, that is, nodes within a distance of $3R_c$ from a source cannot transmit at the same frequency and time slot. If $N_{FREQ} = 1$, then only one node can transmit at a given time slot, resulting in a total of 12 time slots to receive one packet from each source. Therefore, the transmission probability of each node will be $P(t^k_i = 1) = \frac{1}{12} > \frac{1}{N_{intf} \cdot n_k}$. Note that, in this example, $n_k = 6$. On the other hand, if $N_{FREQ} = 2$, then the transmissions along the two paths can be made independently resulting in doubling the transmission probability per node. That is, in this case, $P(t^k_i = 1) = \frac{1}{6} > \frac{2}{N_{intf} \cdot n_k}$.

Next, we evaluate the probability of successful reception, which can be viewed as a condition on the signal to interference and noise ratio $SINR$. Let $P_t$ be the power of node $i$ that is exponentially distributed with mean $\bar{P_t}$. That is, $Pr\{P_t = x\} = \frac{1}{\bar{P_t}} \exp\{-\frac{x}{\bar{P_t}}\}$. Assume $\bar{P_t} = \bar{P} \forall i$. Suppose a transmission is made from $l_i$ to $l_j$, where $l_i$ and $l_j$ are the locations of the transmitting and receiving nodes, respectively, and $L_{i,j} = |l_i - l_j|$ is the distance between them. The SINR in the transmission from $i$ to $j$, $SINR_{i,j}$, can be expressed as $SINR_{i,j} = \frac{L_{i,j} P_t}{N_o + \sum_{x \in X_i} L_{x,j} P_x}$, 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 as node $i$, and $\beta \geq 2$ is the path loss exponent ($\beta = 2$ 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 $\text{SINR}_{i,h} = \frac{L_{i,h} P_i}{N_o}$. Hence, we use $\text{SINR}$ and $\text{SNR}$ interchangeably.

We can write

$$
\Pr \{ r^h_{i,h} = 1 | t^h_{i,h} = 1 \} = \Pr \{ \text{SINR}_{i,h,i_h-1} > \gamma \},
$$

(10)

where $\gamma$ is the SINR threshold for successful transmission.

Note that if the transmitter power is fixed and is affected by a Rayleigh fading channel, the received power will be exponentially distributed [28]. In other words, this model is equivalent to having a fixed-power transmitted signal passing through a Rayleigh fading channel. In both cases, the received SINR will be exponentially distributed [29]. Define $\lambda_{i,h} = \gamma N_0\left[ L_{i,h,i_h-1} \right]^\beta$ as the minimum transmit power of node $i_h$ to guarantee the $\text{SINR}$ threshold at hop $h-1$. We have,

$$
\Pr \{ \text{SINR}_{i_h,i_h-1} > \gamma \} = \Pr \{ P_{i_h} > \lambda_{i,h} \} = \int_{s=\lambda_{i,h}}^{\infty} \frac{1}{s^\beta} \exp \left\{ -\frac{1}{\beta} s \right\} ds = \exp \left\{ -\mu_{i,h} \right\} = \exp \left\{ -\gamma N_0 \frac{1}{P} \left[ L_{i_h,i_h-1} \right]^\beta \right\}.
$$

(11)

Note that the average SNR at hop $h$ can be expressed as:

$$
\text{SNR}_h = \frac{P[F_{i_h,i_h-1}]}{N_o}. \quad \text{If} \quad L_{i_h,i_h-1} = L \forall h, \quad \text{then} \quad \text{SNR}_h = \text{SNR} \quad \text{and} \quad \Pr \{ \text{SINR}_{i_h,i_h-1} > \gamma \} = \exp \left\{ -\frac{\gamma}{\text{SNR}} \right\} \forall h. \quad \text{From} \quad (9) \quad - \quad (11), \quad \text{we get:}
$$

$$
T_{i,k} = \Pr \{ t^k_i = 1 \} \prod_{h=1}^{N^+_k} \exp \left\{ -\gamma N_0 \frac{1}{P} \left[ L_{i_h,i_h-1} \right]^\beta \right\} = \Pr \{ t^k_i = 1 \} \exp \left\{ -\gamma N_0 \frac{1}{P} \sum_{h=1}^{N^+_k} \left[ L_{i_h,i_h-1} \right]^\beta \right\}.
$$

(12)

**Theorem 1.** In a multihop MC-WSN network, assuming exponentially distributed transmit powers, the throughput of CH $i$ along a predefined single routing path to sink $k$ is:

$$
T_{i,k} = \Pr \{ t^k_i = 1 \} \exp \left\{ -\kappa \sum_{h=1}^{N^+_k} \left[ L_{i_h,i_h-1} \right]^\beta \right\},
$$

(13)

where $N^+_k$ is the number of hops in CH $i$’s transmission, $\Pr \{ t^k_i = 1 \}$ is the probability that CH $i$ and all its intermediate relaying nodes are scheduled to transmit the data of CH $i$ to sink $k$, $\beta$ is the path loss exponent of the channel, $L_{x,y}$ is the distance between nodes $x$ and $y$, and $\kappa = \gamma N_0^\beta P$.

**Remark 1.** It can be seen from Theorem 1 that if the hops are equidistant, the throughput will decrease as the number of hops increases. More specifically, when $L_{i_h-1,i_h} = L$, $\forall h \in \{1, 2, \ldots, N_k^+\}$, we get $T_{i,k} \propto \exp \{ -N_k^+ \}$. It follows that $\lim_{N^+ \to \infty} T_{i,k} = 0$.

This result justifies our motivation of limiting the number of hops from each sensor to the MA to a prespecified 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 throughput, delay, security, and energy efficiency.

**Remark 2.** It is worth mentioning that if the distance between the source and the sink is fixed, then larger number of hops would correspond to lower per-hop distance, and consequently resulting in an improved performance at low SNR values. However, this would require higher node density, and hence an increase in the number of nodes in each cell. In this paper, under the assumption that the number of nodes in each cell is fixed, we will mainly consider the case of fixed per-hop distance.

Now we obtain the overall average per node throughput. Define $P_{Ak}$ as the probability that a cluster head lies in the coverage area of sink $k$. That is, its nearest sink is sink $k$. Following Lemma 1, we set $P(t^k_i) = 1 = \frac{N_{\text{Freq}}^+}{{N_{\text{intf}}^+ N_k^+}}$, which is a conservative measure for the per node transmission probability. Recall that $N_{CH}$ is the total number of CHs, then the number of CHs that transmit to sink $k$ is $N_k = P_{Ak} N_{CH}$. Hence, the overall average per node transmission probability in the cell, $P_t$, can be expressed as:

$$
P_t = \sum_{k=0}^{K} P_{Ak} \frac{N_{\text{Freq}}^+}{{N_{\text{intf}}^+ N_k^+}} = \sum_{k=0}^{K} P_{Ak} \frac{N_{\text{Freq}}^+}{{N_{\text{intf}}^+ P_{Ak} N_{CH}^+}} = (K + 1) \frac{N_{\text{Freq}}^+}{{N_{\text{intf}}^+ N_k^+}},
$$

(14)
where $N_{intf}$ is the bandwidth reuse measure, and $N_{FREQ}$ is the number of frequencies available for simultaneous cluster head transmissions. For equidistant hops with length $R_c$, the overall average per node throughput is expressed as

$$T = P_t \exp \left\{ -\kappa N_{hop} R_c^4 \right\},$$

(15)

where $N_{hop}$ is the average number of hops from a CH to its corresponding sink in each cell, and is obtained in Section III.

C. Multihop Multipath Routing Case

In the previous subsection, we considered the case when there is a single pre-defined path between a CH and a sink. Note that, in general, the transmission can go through different paths due to the existence of network diversity. In this section, we formulate the throughput for the multipath case. We have the following result:

**Theorem 2.** Let $N$ be the maximum number of hops from a CH to its sink along any routing path. Consider that for each hop number $l \in \{1, 2, ..., N\}$, there are $P_{l,i}$ possible $l$-hop paths from CH $i$ to sink $k$. Let $T(i|N_i^k = l, \mathcal{P}_i^k = p)$ be the throughput that can be achieved along one of the $l$-hop paths from source $i$ to sink $k$ assuming the path $\mathcal{P}_i^k = p$, then the throughput of node $i$ can be calculated as:

$$T_{i,k} = \sum_{i=1}^{N} \sum_{p=1}^{P_{l,i}} T(i|N_i^k = l, \mathcal{P}_i^k = p) \Pr\{\mathcal{P}_i^k = p|N_i^k = l\} \times \Pr\{N_i = l\}.$$  \hspace{1cm} (16)

Here, $l$-hop path means a path that consists of $l$ hops. It is noted that $T(i|N_i^k = l, \mathcal{P}_i^k = p)$ can be obtained from Theorem 1 by substituting $N_i^k = l$, which is the number of hops along the particular path $\mathcal{P}_i^k = p$. The term $\Pr\{\mathcal{P}_i^k = p|N_i^k = l\}$ depends on the routing protocol. It should be emphasized that when multiple routes are enabled, the utilized scheduling protocol, and hence $P(t_i^k = 1)$, could be different than that in the single routing path case.

D. Total Network Throughput

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

Let $\mathcal{N}_i^k$ be the set of CHs that transmit to sink $k$. Following Theorems 1 and 2, the total throughput of the proposed MC-WSN architecture with $K$ RCHs and a CCH can be obtained as:

$$\Upsilon = \sum_{k=0}^{K} \sum_{i \in \mathcal{N}_i^k} T_{i,k} = \sum_{k=0}^{K} \sum_{i \in \mathcal{N}_i^k} \sum_{l=1}^{N} \sum_{p=1}^{P_{l,i}} T(i|N_i^k = l, \mathcal{P}_i^k = p) \times \Pr\{\mathcal{P}_i^k = p|N_i^k = l\} \times \Pr\{N_i = l\}.$$  \hspace{1cm} (17)

where $n_k$ is the number of nodes connected to sink $k$, $L_{i_h^k,i_{h-1}^k}(p)$ is the length between CHs $i_h^k$ and $i_{h-1}^k$ along path $p$, and $p_{i_h^k}(p)$ is the transmission probability of CH $i$ along path $p$ to sink $k$.

V. MC-WSN WITHIN A BIGGER VISION — CONVERGENCE OF CENTRALIZED AND AD-HOC NETWORKS

In this section, we provide a more fundamental reasoning for the design of MC-WSN from the network evolution perspective.

A. Convergence of Centralized and Ad-Hoc networks — a Revisit

Represented by the cellular networks, centralized networks have been playing a dominant role in wireless communication system management and deployment. Cellular networks have evolved from the 1G voice centric system, represented by the Advanced Mobile Phone System (AMPS) and European Total Access System (ETACS), to today’s high speed multi-media 3G (UMTS WCDMA, CDMA 2000 and TD-SCDMA) and 4G (WiMAX and LTE) systems.

With well-organized infrastructure, centralized networks can provide very good transmission reliability, efficiency and scalability. However, the traditional centralized network does not have sufficient diversity and end-point communication flexibility. For example, in today’s cellular networks, the mobile will generally lose network connection once the BS is not functioning, since each mobile is typically connected to only one BS. Moreover, if two mobiles are spatially close, they cannot establish direct communication, but have to communicate through the BS, leading to unnecessary resource waste.

The structureless ad-hoc networks, on the other hand, can provide excellent flexibility with reliable performance for small-scale networks. One good example is the mesh network, where direct (one-hop) communication can be established between any two end-points within the local area network. The scalability, however,
has proved to be a serious challenge for large-scale ad-hoc networks due to the uncertainty, complexity, as well as the delay and energy concerns in the routing process. The problems become even worse when the devices are mobile.

The observations above lead to the idea of hybrid networks, which actually reflects the convergence of centralized and ad-hoc networks. On the cellular side, recent wireless MAN and LAN standards, such as WiMAX 802.16 and WiFi 802.11s, have incorporated the mesh capability to the wireless network nodes, which allows each node to forward the traffic of other nodes in the network in a planned yet ad-hoc manner. On the ad-hoc side, local structures are inserted to the network for more efficient and simpler transmissions. More specifically, the end points are grouped into clusters, with each cluster managed by a cluster head in a centralized manner. This idea leads to the mobile ad-hoc network (MANET) and clustered wireless sensor networks.

The evolution of the centralized and ad-hoc networks to hybrid networks indicates that: for wireless communications, we would need both network centric management as well as ad-hoc flexibility. Based on this observation, we can summarize the general network design criterions as follows: The network needs to have a well-organized infrastructure to ensure the reliability (including both transmission accuracy and security), capacity, energy efficiency as well as time efficiency. At the same time, the network should provide sufficient flexibility by allowing authorized ad-hoc communications among the nodes or devices.

B. The Idea of the N-hop Networks

With the general design criterions in mind, we now try to come up with a unified framework for wireless networks that could cover most of the existing systems as special cases.

For any wireless network, let the minimum number of hops for a basic node (i.e., the terminal, such as a mobile or a sensor) $i$ to reach the base station (BS) or the sink be $N_i$. Define $N = \max\{N_i\}$ over all the nodes. $N$ is an important characterization on how closely the basic nodes are connected to the BS or the sink. It has a direct impact on network capacity, reliability, delay, efficiency, as well as their evaluation techniques.

Now we introduce the idea of $N$-hop networks. A wireless network is said to be an $N$-hop network if every basic node (BN) can reach the BS or the sink within $N$ hops under normal network conditions. By normal conditions, we mean that there are no hostile attacks, or severe, unexpected system failures. Based on this definition, if $N = 1$, we obtain the strictly centralized network. For some sensor networks with mobile access points, we also have $N = 1$, see the SENMA in [1] for example. In SENMA, with well designed mobile access trajectory, there is no routing and all the sensors can reach the mobile access in one hop. If $N = 2$, we get the relay-assisted cellular network; For an ad-hoc network of size $n$, generally, $N \leq n - 1$. Actually, almost all the existing systems fall into this unified framework.

C. MC-WSN, Hop Number Control and Further Discussions

MC-WSN provides an interesting and representative example on N-hop hybrid network design. A main feature of MC-WSN is that the number of hops from any sensor to the mobile access can be limited to a pre-specified number $N$ through active network deployment and topology design.

The importance of the hop number control was justified in Section IV, the throughput analysis. First, it was shown that along each individual path where the hops are equidistant, the throughput decreases as the number of hops increases; Second, the N-hop framework makes it possible for us to obtain a quantitative form for the throughput calculation of each node in the flexible, multipath scenarios. More specifically, the throughput is obtained as the sum of the weighted throughput of all possible paths, where the weight of a path is the probability for the path to be selected for transmission. That is, with the N-hop framework, analytical evaluation of the network performance becomes more tractable.

Discussion on Future Work Due to possible link failure conditions and/or malicious attacks, the number of hops for a node to reach the sink could be more than $N$. For this reason, we extend the definition of N-hop networks to $\alpha$-level $N$-hop networks, which is characterized by: $Pr\{\text{BN can reach the BS or sink within N hops}\} = \alpha$. The level $\alpha$ can be used as an indicator of how smooth the network is operating.

This extension leads us to a more complex and challenging field — secure and efficient network design and analysis under various hostile environment.

VI. Numerical 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 per node throughput performance of the MC-WSN, and compare it to that of SENMA.

We assume that the SNs and CHs are uniformly distributed in each cell, and TDMA/FDMA is used for scheduling. In the simulations, we use the following parameters: the communication range of the cluster
heads is $R_e = 30m$ and that of sensors is $r_c = 15m$, the optimal values for $R_o$ and $R_i$ are set according to Proposition 1, the path loss exponent is $\beta = 2$, the $SINR$ threshold is $\gamma = 5dB$, and the bandwidth reuse measure is $N_{intf} = 2$. Assuming the packet size is 16 bytes and the data rate is 5kbps, then the packet duration will be 25.6ms. The slot duration equals to the packet duration, i.e., we set $T_{slot} = 25.6ms$. Note that the same slot duration will be needed if the packet size is 128 bytes, and the data rate 40kbps.

**Example 1: Hop number control** Figure 4 shows the average number of hops and the maximum number of hops versus the number of RCHs ($K$) in MC-WSN. As expected, when $K$ increases, the 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 $\frac{2d}{\pi R_e}$. Under the same settings used in Figure 4, it is clear that data transmission in MC-WSN can be performed effectively through less number of hops as compared to the traditional centralized network model with a single sink.

**Example 2: Throughput comparison** In this example, we evaluate the overall average per node throughput of MC-WSN and compare it to that of SENMA for different network cell sizes $d$. Define the density of the sensor nodes and the cluster heads as $\rho SN = \frac{n}{\pi d^2}$ and $\rho CH = \frac{N_{MA}}{\pi d^2}$, respectively. Here, we set $\rho SN = 0.0283$, $\rho CH = 0.0014$, and assume $SNR = 8dB$. In SENMA, the transmission probability of any sensor can be evaluated as: $P(t_{SENMA} = 1) = \frac{T_{slot}}{T_{MA}} + nT_{slot}$, where $V_{MA}$ is the speed of the MA, $L_{MA}$ is the length of the MA trajectory, and $T_{slot}$ is the slot duration assigned to each node for transmission. We set $V_{MA} = 30m/s$, which is relatively high. The length of the MA trajectory in SENMA can be expressed as: $L_{MA} = 2\pi \sum_{i=0}^{n-1} (d - (2l + 1)r_c) + 2r_c(\left\lceil \frac{d}{r_c} \right\rceil - 1)$ [30].

In Figure 5, the overall average per node throughput of MC-WSN with $K = 6$ and SENMA architecture are plotted versus the network cell radius. For MC-WSN, we consider the cases when $N_{Freq} = 1$ and $4$. It is shown that the throughput of MC-WSN is superior to that of SENMA. This is because the transmission of the nodes in the SENMA architecture depends on the speed of the MA and its trajectory length. It can be seen from Figure 5 that as the number of orthogonal frequencies increases, the throughput of MC-WSN can be further improved.

**Example 3: Throughput performance under non-ideal network settings** In this example, we will take both the collision effect and non-ideal network deployment into consideration, and explore how that would influence the throughput performance. In the network setup, we deploy CHs in layers with respect to the CCH and the interval between neighboring layers is $R_e$. The CHs in each layer are uniformly distributed on a circle according to density $\rho_{CH}$. We then introduce Gaussian noise to the positions of CHs, and obtain non-uniform CH deployment. We assume shortest path routing among the CHs. The network deployment and routing paths are shown in Figure 6, where the radius of the region is $d = 200m$.

In the simulation, we assume that: (i) during an initial network set-up phase, the basic nodes (i.e., the sensor nodes) within each cluster are informed about their
schedules to transmit to the corresponding cluster head; and the cluster heads surrounding the powerful Ring Cluster Heads (RCHs) or Center Cluster Head (CCH) are informed about their schedules to transmit to the corresponding RCH or CCH, respectively. (ii) For the ad-hoc routing among cluster heads before the packets reach the RCHs or CCH, Carrier Sense Multiple Access (CSMA) is used. That is, for each relay CH, the nearby CHs would first verify the absence of traffic in the channel before transmission. Once a CH detects that the channel is busy, it waits for a random period and then try again. The waiting time of each CH is exponentially distributed and its mean is proportional to the inverse of the number of CHs it relays. Statistically, CHs that relay the same number of packets will have equal opportunity of transmission. Here, the overhead is represented as: a control channel is allocated for medium access control (MAC).

In the simulation, the collision effect or interference between clusters that use the same channel or frequency band is taken into consideration. More specifically, we assume that neighboring CHs with distance smaller than $N_{intf} \times R_c$ from the active CH can participate in the CSMA, and will not cause interference. However, for the CHs out of that region, they could not participate in the CSMA and may act as interferers. We take the interference from these CHs into consideration while measuring SNR in our simulation. We set $r_{CSMA} = N_{intf} R_c$, $N_{Freq} = 1$, and keep other parameters the same as in Example 2. The comparison of the theoretical and simulation results is shown in the Figure 7.

Example 4: Energy consumption  Energy efficiency is a primary concern in wireless sensor networks due to the limited power resource of the individual sensors. The hierarchical node deployment in MC-WSN allows sensors to communicate with their nearest CHs only, and hence achieves low energy consumption at the individual sensors, which is much more efficient than the conventional SENMA architecture. In SENMA, all sensors within the coverage area of an MA receives a beacon signal from the MA, which is used to notify sensors of the presence of the MA and to indicate which sensor can transmit. The periodic reception of beacon signals from MA in SENMA contributes significantly to the power consumption at the individual sensors.

To evaluate the energy efficiency, we use the circuitry radio energy dissipation modeling [31]. In this model, each receiving node consumes $E_{rx}$ (J/bit) in the receiver electronics, and each transmitting node consumes $E_{tx} + \epsilon_{pa} L^\beta$ (J/bit), where $E_{tx}$ is the energy dissipated in the transmitter electronics, $\epsilon_{pa}$ is the energy consumed by the power amplifier, $\beta$ is the path loss exponent, and $L$ is the per-hop distance.

Now focusing on the energy consumption at the individual sensors, we find that in MC-WSN the maximum energy dissipated in a sensor to transmit a bit to its corresponding CH is:

$$E_{SN,M} = E_{tx} + \epsilon_{pa} r_c^\beta \quad (J/bit).$$  \hspace{1cm} (18)

In the case of SENMA, each sensor must first receive a beacon signal from the MA in order to report its data. Assuming that the access point traverses the network at a height $H_S$ broadcasting beacon signals at random locations, and modeling the coverage area of the access point as a circle of radius $r$, then the energy dissipated by a sensor to report a single bit to the MA is [1]:

$$E_{SN,S} = E_{rx} + \epsilon_{pa} H_S^\beta + E_{rx} \pi r^2 \frac{n}{A_T},$$  \hspace{1cm} (19)
where $A_T$ is the area of the cell and $n$ is the total number of sensors in this area. Notice the additional term for the reception process in (19) compared to (18). That is, even if $r_c^\beta = H_S^\beta$, the energy consumption in SENMA is higher than that in MC-WSN.

It can be seen from Figure 8 that MC-WSN is significantly more energy-efficient than SENMA, and the energy efficiency gains increase as the density of the sensors increases. The energy dissipated during the multiple beacon reception process contributes significantly to the overall energy consumption in SENMA.

![Figure 8](image)

**Fig. 8.** The energy dissipation (J/bit) vs. the number of SNs in the MC-WSN and SENMA networks, when $r_c = r = 15m$, $H_S = 10m$, $\beta = 2$, $E_{tx} = E_{rx} = 50$ nJ/bit, $\epsilon = 10$ pJ/bit/m$^2$, and $d = 200m$.

### VII. Conclusions

In this paper, a mobile access coordinated wireless sensor networks (MC-WSN) architecture was proposed for reliable, efficient, and time-sensitive information exchange. 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.

**APPENDIX A**

**Transmission Probability**

**Proof of Lemma 1:** In this appendix, we obtain the uniform transmission probability of CHs within the coverage area of sink $k \in [0, 1, \ldots, K]$. We show that when hybrid TDMA/FDMA is used, the transmission probability $P(t^{k^i}_i = 1)\geq N_{\text{freq}} n_k$, $\forall i \in N^k$, where $n_k$ is the number CHs transmitting to sink $k$, $N^k$ is the set of CHs within the coverage area of sink $k$, $N_{\text{freq}}$ is the bandwidth reuse measure, and $\eta_{\text{freq}}$ is the number of frequencies available for simultaneous CHs transmissions within the same interference region.

The length of the TDMA schedule is the number of slots needed for the sink to receive one packet from all CHs within its coverage area. Since CHs within one hop from the sink relay the traffic of all other CHs within the sink’s coverage area, then the largest length of a scheduling period can be obtained by finding the number of slots these CHs need to forward all the traffic they have (one packet from each source) to the sink. Here, we assume that each node has a packet to transmit and all packets are of the same importance, i.e. periodic data collection is considered. Note that in event driven scenarios, the length of the TDMA schedule could be less than that in the periodic data collection case.

First, consider $\eta_{\text{freq}} = 1$. Then, a CH close to the sink can transmit only if other CHs within the interference region are silent. Hence, the length of the transmission schedule to sink $k$ is:

$$S_k \leq \sum_{h=1}^{N_{\text{freq}}} n_{h,k}(N_{f,h,k} + 1),$$

where $n_{h,k}$ is the number of CHs at hop level $h$ from sink $k$, and $N_{f,h,k}$ is the number of CHs that forward their data through CH at hop level $h$ from sink $k$; hence, $(N_{f,h,k} + 1)$ is the total number of packets a node at hop level $h$ sends to sink $k$. Note that the inequality is mainly due to considering the largest number of interfering neighbors, which is when a CH arbitrary close to the sink location is considered.

Recall that $N_{CH}$ is the total number of CHs in the cell. Let $A_T$ be the total area of the cell, and $A_k$ be the coverage area of sink $k$; then, $A_k = \frac{A_T}{N_{CH}}$. Let $A_{h,k}$ be the area served by sink $k$ until hop level $h$ only. Hence, we have:

$$n_{h,k} \simeq \frac{(A_{h,k} - A_{h-1,k})}{A_T} N_{CH}, \quad N_{f,h,k} \simeq \frac{A_k - A_{h,k}}{A_T} \frac{N_{CH}}{n_{h,k}}$$
When $N_{\text{inf}} = 2$, it follows from (A-1) that [17]:

$$S_k \leq n_k \left( 2 - \frac{A_{1,k}}{A_k} \right). \quad (A-3)$$

Since $A_{1,k} < A_k$, then $0 < \frac{A_{1,k}}{A_k} < 1$, and we have $S_k \leq 2n_k$. Similarly, for general $N_{\text{inf}}$, we have:

$$S_k \leq N_{\text{inf}} n_k. \quad (A-4)$$

Note that if one of the nodes within one hop from sink $k$ transmits the data of CH $i$ to the sink, this would mean that all intermediate CHs within the routing path from $i$ to the sink have transmitted this data, i.e., $Pr\{t_{ik} = 1\} = Pr\{t_{ik}^1 = 1, \ldots, t_{ik}^N = 1\} = Pr\{t_{ik} = 1\}$. In other words, within a schedule period of length $S_k$, all CHs would have transmitted their packets to the sink. Hence, the transmission probability $P(t_{ik}^1 = 1) = \frac{1}{N_{\text{inf}} n_k}$. Thus, $P(t_{ik}^1 = 1) \geq \frac{N_{\text{Freq}}}{N_{\text{inf}} n_k}$. For general $N_{\text{Freq}}$, we have

$$P(t_{ik}^1 = 1) \geq \frac{N_{\text{Freq}}}{N_{\text{inf}} n_k}. \quad (A-5)$$

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