This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSIPN.2016.2601021, IEEE Transactions on Signal and Information Processing over Networks

Mobile Access Coordinated Wireless Sensor Networks – Design and Analysis

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***Abstract*—This paper introduces and analyzes a novel mobile access coordinated wireless sensor network (MC-WSN) architecture. In conventional sensor networks with mobile access points (SENMA), the mobile access (MA) points 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, first, we discuss the optimal topology design for MC-WSN such that the average number of hops between the source and its nearest sink is minimized. Second, we calculate the throughput of MC-WSN and illustrate the effect of the number of hops on the throughput. Third, we establish the queuing model for the cluster heads based on the Kleinrock independence assumption and Burke's theorem, and show that the traffic at each cluster head can be modeled as an independent M/M/1 queue. Finally, based on the queue modeling, we provide an in-depth analysis on network stability, delay, and energy efficiency. Our analysis is demonstrated through numerical results. It is shown that under stable system conditions, MC-WSN achieves much higher throughput and considerably lower delay and energy consumption over SENMA.**

***Index Terms*—Wireless sensor networks, mobile access coordinator, throughput, stability, delay, energy efficiency.**

I. Introduction

Wireless sensor networks (WSNs) have been identified as a key enabling technology for various military and civilian 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 [5]. SENMA can relocate energy expensive tasks, such as routing functions, to the MA, and hence improves the energy efficiency of the individual sensor nodes over ad-hoc networks.

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. This makes SENMA undesirable for time-sensitive applications.

In addition to SENMA, there exist several network models that use UAVs to assist in information gathering from sensor nodes. Joint sink mobility and multihop routing to the sink is presented in [6], where the main objective is to achieve balanced loads at each of the sensors to improve the lifetime of the network. There are many models that simplify the trajectory of the MA by having it visit only few number of predefined locations [2], [7], and nodes route their data to one of these locations where data is stored until the MA visit. In [8], to maximize the lifetime of a network with a mobile sink, authors studied the time duration that a sink spends at a single location as well as the rate of transmission between nodes based on the sink's location. In [9], it is assumed that few nodes in the network have the knowledge of the sink location, and when an arbitrary node needs to reach the MA, it first acquires the sink location then routes its data accordingly. Other models update the trajectory of the UAVs based on the location of the cluster heads in the ground sensor network [10], [11], where the cluster heads are dynamically selected based on their dissipated energy.

For most existing approaches, (i) similar to the conventional SENMA, the network performance depends on the speed of the access points, which would result in large delays and/or communications overhead that are unacceptable in time-sensitive information exchange; (ii) most existing models rely on the continuous traversal of the access points over the network. Hence, if for any reason an MA has to stop for recharging, for example, data transfer would be disturbed; (iii) many network models implicitly assume that the primary objective of the MAs' travel is in data collection. When the WSN is employed in unattended areas, it is highly desirable if the MA can coordinate the network, maintain its function, and ensure the network operation even when it is deployed in a hostile environment. Hence, a novel network architecture is needed to

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This work was partially supported by the National Science Foundation under Grants CNS-1217206 and ECCS-1232109.

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ensure time-sensitive information exchange that is independent of the physical speed and the trajectory of the MA, and keep critical network management functions uninterrupted.

As an effort to solve this problem, we propose a novel mobile access coordinated wireless sensor network (MC-WSN) architecture 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 in 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.

In this paper, we first present the MC-WSN architecture development and topology design, then analyze the network in terms of throughput, stability, delay, and energy efficiency by exploiting tools in information theory, queuing theory, and radio energy dissipation modeling.

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 [12]–[18], including one-hop centralized cases [12], [13] and ad-hoc cases [14]–[16]. There are also research on systems with mobile nodes [19], [20] and systems with mobile access points, like SENMA [1].

In [14], 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 $O(\frac{W}{\sqrt{n}})$ 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 [21]. 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 [22], [23]. 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 this paper, we analyze the throughput of MC-WSN under both single path and multiplath 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 is orders of magnitude higher than that of the conventional SENMA.

For stability and delay analysis, the major challenge lies in the dependency among different queues along the routing path. For example, we have dependency between the inter-arrival times (which measures the time difference between two successive arrivals) and service times at each of the intermediate queues, and dependency between service times at different queues. Due to these dependencies, network analysis becomes highly complicated and intractable. Fortunately, it was observed that when the network is densely connected with moderate to heavy traffic loads, the dependencies between the inter-arrival times and service times can be eliminated by merging or multiplexing multiple packet streams at each link. This is known as the *Kleinrock independence assumption*, and has shown to be a valid model for network analysis [24]. In this paper, based on the *Kleinrock independence assumption* and queuing modeling/analyzing theorems (mainly *Burke's theorem* and *Little's theorem* [25]), we establish the queuing model for the CHs in MC-WSN, analyze the stability and delay of the network, and highlight their relationship with the throughput.

It can be shown that the network throughput, stability, and delay are closely related. More specifically, for a system to be stable, the arrival rate at each node cannot be larger than the service rate, which is bounded by the corresponding throughput. At the same time, to ensure bounded delay in a transmission, the system has to be stable.

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. 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 through heterogeneous node deployment.
- 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, when the signal-to-noise ratio (SNR) is fixed and the hops are equidistant, the throughput diminishes exponentially

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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 establish the queuing model for the cluster heads based on the *Kleinrock independence assumption* and *Burke's theorem*. We prove that the traffic at each CH can be modeled as an independent M/M/1 queue, by showing that: (i) the service process of each queue can be modeled as a Poisson process and is independent from node to node; (ii) the arrival process at each queue can be modeled as a Poisson process. We calculate the arrival rate and service rate of the individual CHs, and derive the necessary conditions for the stability of MC-WSN. It is shown that the system stability largely relies on the arrival rate and the throughput, which maps to conditions on scheduling, number of channels, signal-to-noise ratio, as well as the bound on the number of CHs that can be served by each sink (either CCH or RCH).
- We conduct delay analysis for MC-WSN and calculate the average delay for a packet to reach its nearest sink in both single path case and multipath case. It is shown that the hop number control and the network uniformity achieved by MC-WSN can largely simplify the delay analysis.
- We provide energy efficiency analysis based on the radio energy dissipation modeling. Since the sensors are relieved from the energy consuming routing functions and the periodic reception of control signals from the mobile access point, MC-WSN has significantly higher energy efficiency than the conventional SENMA.

Our analysis is demonstrated through numerical results. It is shown that under stable system conditions, MC-WSN achieves much higher throughput and considerably lower delay and energy consumption over 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 MC-WSN Architecture and Topology Design

A. MC-WSN Architecture

MC-WSN is a hierarchical and heterogeneous network, where sensor nodes (SNs) are arranged into clusters each is managed by a cluster head (CH) that routes the sensors' information to a mobile access point (MA) through a powerful center cluster head (CCH) or a ring cluster head (RCH) [26], [27]. Each sensor communicates directly with its corresponding CH and is not involved in the routing process. 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. Under normal operation, RCH and CCH communicate directly to the MA. If for any reason, an RCH cannot establish a communication with the MA, it can also transmit through other RCHs 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. 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.

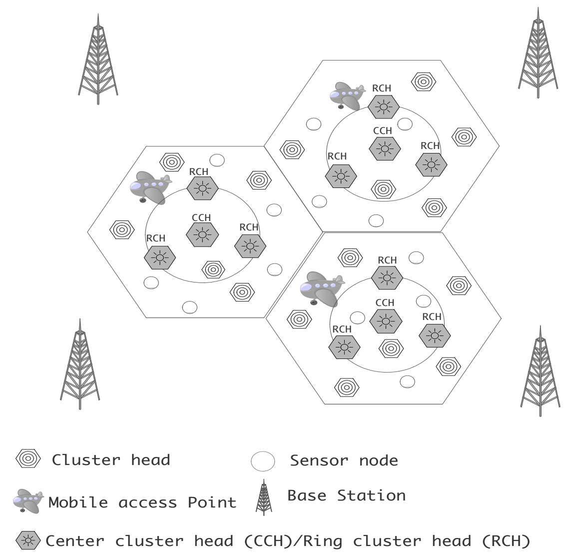

Fig. 1. Proposed MC-WSN architecture.

In the 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. 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 [28]. 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. CHs and SNs that are within the MA's coverage area can transmit their data directly to the MA. Note that the sensors are not involved in the inter-cluster routing, so as 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. 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.

B. MC-WSN Topology Design and Hop Number Control

The number of hops in data transmission has a direct impact on the network performance. More specifically, under the same channel conditions, as the number of hops increases, the throughput decreases and the delay increases, as will be seen in Sections III and IV. That justifies our motivation in the topology design and RCHs deployment, which is to minimize the number of hops from any CH to the corresponding CCH/RCH. Note that since the number of hops from a sensor to its CH is one, and the number of hops from a CCH or an RCH to the MA in the cell is also one, then minimizing the number of hops between any CH and its corresponding CCH/RCH is equivalent to minimizing the number of hops from a sensor to the MA. The main result of the network topology design is summarized in the following proposition.

Proposition 1. *Assuming a circular cell of radius d, to minimize the number of hops in the MC-WSN architecture with one CCH and K RCHs, where $K > 2$, data transmission should be arranged as follows: (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) 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 $R_t = 0.233K\sin(\frac{\pi}{K})d$.*

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

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

where x is the distance from any CH to the center of the cell, and θ is the angle from the CCH, as illustrated in Figure 2. Here, $f_X(x)$ is the probability density function (PDF) of x. Assuming that the CHs are uniformly distributed in a circle of radius d, then $f_X(x)$ can be approximated by $f_X(x) = \frac{2x}{d^2}$, and the PDF of θ is modeled as $f_\theta(\theta) = \frac{1}{2\pi}$, $\forall\theta \in [0, 2\pi]$.

Set
$$\frac{\partial\bar{d^2}}{\partial R_o} = 0, \quad \frac{\partial\bar{d^2}}{\partial R_t} = 0. \tag{2}$$

We get the optimal $R_o = \frac{\pi R_t}{2K\sin(\frac{\pi}{K})}$, and $R_t = \frac{\sqrt{3}-1}{\pi}K\sin(\frac{\pi}{K})d = 0.233K\sin(\frac{\pi}{K})d$. It follows that $R_o = 0.366d$. □

Note that here we try to minimize the number of hops in a transmission under a fixed per-hop distance and fixed node density. The node density is selected to provide sufficient diversity to ensure that each node can reach a sink with minimum number of hops. If the per-hop distance is variable and the node density could be increased, then the number of hops could be optimized to account for possible trade-offs between energy efficiency, delay, and throughput [29].

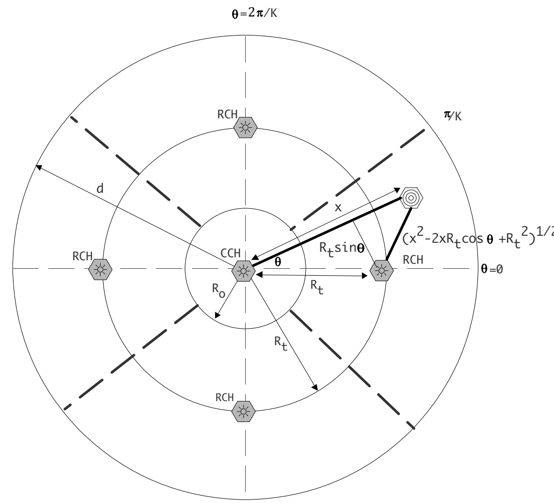

Fig. 2. MC-WSN with four powerful RCHs.

Hop Number Control: Assuming shortest path routing, the maximum number of hops from any sensor to the MA when the average per-hop distance is R_c can be expressed as:

$$N = 2 + \left\lceil \frac{1}{R_c}\max\left\{R_o, \sqrt{R_o^2 - 2R_oR_t\cos(\frac{\pi}{K}) + R_t^2},\right.\right.$$
$$\left.\left.\sqrt{d^2 - 2dR_t\cos(\frac{\pi}{K}) + R_t^2}\right\}\right\rceil, \tag{3}$$

where the first term accounts for the number of hops from a sensor to its corresponding CH and from a sink (CCH/RCH) to the MA. As can be seen, the maximum number of hops can be limited to a pre-specified number through the deployment of RCHs and the topology design. More specifically, N can be managed by the choice of the number of RCHs K, cell radius d, ring radius R_t, and the radius R_o.

Remark 1. *Recall that K is the number of RCHs. In Proposition 1, $K > 2$ is assumed to make the nodes at the border of a cell have lower number of hops to a RCH than to a CCH. The cases of $K = 1, 2$ are discussed in Appendix A.*

III. Throughput Analysis

In this section, we provide the throughput analysis of for MC-WSN, and show the effect of the number of hops on the network throughput performance.

A. Definition of the Throughput

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 [30]. Let t_i^k be a binary flag indicating that node i transmits data to sink k: $t_i^k = 1$ means that node 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). Assume that the packet reception from slot to slot is an i.i.d process, then the throughput can be formulated as:

$$T_{i,k} = Pr\{r_i^k = 1 | t_i^k = 1\} Pr\{t_i^k = 1\}. \quad (4)$$

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 Medium Access Control (MAC) protocol. Thus, we focus on data transmission from the CH of the originating node to its corresponding CCH/RCH.

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 $\tilde{X}_i^k$ be the non-zero packets of X_i^k, then $X_i^k = t_i^k \tilde{X}_i^k$ [12]. Assume that sink k receives packets from multiple nodes in a collision-free manner. Define $\mathbf{Y}^k$ as the received vector at sink k, where the ith element in $\mathbf{Y}^k$ is the received packet from CH i. Let $\mathbf{r}^k$ be the vector whose ith element is r_i^k. It has been shown in [12] that the mutual information between X_i^k and $\mathbf{Y}^k$ can be written as a function of the throughput of CH i to sink k ($T_{i,k}$) as follows:

$$\mathbf{I}(X_i^k, \mathbf{Y}^k) = \mathbf{I}(t_i^k, \mathbf{r}^k) + H(\tilde{X}_i^k) T_{i,k}, \quad (5)$$

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

From the information theory perceptive, it can be seen 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

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 $i_{N_i^k} \to i_{N_i^k - 1} \to ... i_1 \to i_0$, where $i_{N_i^k}$ is the source CH i and i_0 is the sink k. Let $t_{i,h}^k$ 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 $r_{i,h}^k$ 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 time slot, we have:

$$Pr\{r_{i,h}^k = 1\} = Pr\{r_{i,h}^k = 1 | t_{i,h}^k = 1\} Pr\{t_{i,h}^k = 1\}. \quad (6)$$

Consider that a packet of CH i is received at sink k in slot ν. This implies that there exists a scheduling slot vector $\boldsymbol{\nu} = [\nu - \Delta\nu_{N_i^k - 1}, ..., \nu - \Delta\nu_1, \nu]$, 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 $\boldsymbol{\nu}$, define the transmission flag of CH i as $t_i^k(\boldsymbol{\nu})$, such that $t_i^k(\boldsymbol{\nu}) = [1, .., 1]$ when CH i transmits a packet to sink k and the transmission at the last hop (at CH i_1) occurs in slot ν. 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

$$Pr\{t_i^k(\boldsymbol{\nu}) = 1\} = Pr\{t_{i,1}^k(\nu) = 1, ..., t_{i,N_i^k}^k(\nu - \Delta\nu_{N_i^k - 1}) = 1\}. \quad (7)$$

Omit the slot index, (7) can be simplified as: $Pr\{t_i^k = 1\} = Pr\{t_{i,1}^k = 1, ..., t_{i,N_i^k}^k = 1\}$.

For the throughput calculation here, we do not consider re-transmissions 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 $r_{i,h}^k$'s are independent at different hops, it follows from (4) and (6) that:

$$\begin{aligned} T_{i,k} &= Pr\{t_{i,1}^k = 1, ..., t_{i,N_i^k}^k = 1\} \prod_{h=1}^{N_i^k} Pr\{r_{i,h}^k = 1 | t_{i,h}^k = 1\}, \\ &= Pr\{t_i^k = 1\} \prod_{h=1}^{N_i^k} Pr\{r_{i,h}^k = 1 | t_{i,h}^k = 1\}. \end{aligned} \quad (8)$$

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.

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 [18], we have the following result.

Lemma 1. *When TDMA is used, each node connected to sink k can transmit with a probability $P(t_i^k = 1) \geq \frac{1}{N_{intf} \ n_k}$. 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 $P(t_i^k = 1) \geq \frac{N_{Freq}}{N_{intf} \ n_k}$.*

We now evaluate *the probability of successful reception*, which can be viewed as a condition on the signal to interference and noise ratio $SINR$. Let P_i be the received power at unit transmission distance of the signal transmitted by node i, which is exponentially distributed with mean $\bar{P}_i$. That is, $Pr\{P_i = x\} = \bar{P}^{-1} \exp\{-\bar{P}^{-1} x\}$. Assume $\bar{P}_i = \bar{P}$ $\forall i$. 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 $SINR_{i,j} = \frac{L_{i,j}^{-\beta} P_i}{N_o + \sum_{x \in X^i, x \neq i} L_{x,j}^{-\beta} P_x}$, where N_o is the noise power, X^i is the set of all radios transmitting

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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 $SINR_{i,j} = \frac{L_{i,j}^{-\beta} P_i}{N_o}$. Hence, we use $SINR$ and SNR interchangeably.

We can write

$$Pr\{r_{i,h}^k = 1 | t_{i,h}^k = 1\} = Pr\{SINR_{i_h, i_{h-1}} > \gamma\}, \tag{9}$$

where γ 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 [31]. 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* [32]. Define $\lambda_{i,h} = \gamma N_o \left[L_{i_h, i_{h-1}}\right]^\beta$ as the minimum P_{i_h} to guarantee that the $SINR$ is above the threshold at hop $h-1$. We have,

$$\begin{aligned} Pr\{SINR_{i_h, i_{h-1}} > \gamma\} &= Pr\{P_{i_h} > \lambda_{i,h}\} \\ &= \exp\left\{-\gamma \frac{N_o}{\bar{P}} \left[L_{i_h, i_{h-1}}\right]^\beta\right\} \end{aligned} \tag{10}$$

From (8) - (10), we get

$$\begin{aligned} T_{i,k} &= Pr\{t_i^k = 1\} \prod_{h=1}^{N_i^k} \exp\left\{-\gamma \frac{N_o}{\bar{P}} \left[L_{i_h, i_{h-1}}\right]^\beta\right\} \\ &= Pr\{t_i^k = 1\} \exp\left\{-\gamma \frac{N_o}{\bar{P}} \sum_{h=1}^{N_i^k} \left[L_{i_h, i_{h-1}}\right]^\beta\right\}. \end{aligned} \tag{11}$$

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

$$T_{i,k} = Pr\{t_i^k = 1\} \exp\left\{-\kappa \sum_{h=1}^{N_i^k} \left[L_{i_h, i_{h-1}}\right]^\beta\right\}, \tag{12}$$

where N_i^k is the number of hops in CH i's transmission, $Pr\{t_i^k = 1\}$ is the probability that CH i and all its intermediate relaying nodes are scheduled to transmit the data of CH i to sink k, β is the path loss exponent of the channel, $L_{x,y}$ is the distance between nodes x and y, and $\kappa = \gamma \frac{N_o}{\bar{P}}$.

Note that the average SNR at hop h can be expressed as: $\overline{SNR}_h = \frac{\bar{P}\left[L_{i_h, i_{h-1}}\right]^{-\beta}}{N_o}$. If $L_{i_h, i_{h-1}} = L \ \forall h$, then $\overline{SNR}_h = SNR$ and $Pr\{SINR_{i_h, i_{h-1}} > \gamma\} = \exp\left\{-\frac{\gamma}{SNR}\right\} \ \forall h$. Hence, the throughput

$$T_{i,k} = Pr\{t_i^k = 1\} \exp\left\{-N_i^k \frac{\gamma}{SNR}\right\}. \tag{13}$$

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

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

Average Per Node Throughput: Define P_{A_k} 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 $P(t_i^k = 1) = \frac{N_{Freq}}{N_{intf} \ n_k}$, 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 $n_k = P_{A_k} N_{CH}$. Hence, the overall average per node transmission probability in the cell, $\bar{P}_t$, can be expressed as:

$$\begin{aligned} \bar{P}_t &= \sum_{k=0}^{K} P_{A_k} \frac{N_{Freq}}{N_{intf} \ n_k} = \sum_{k=0}^{K} P_{A_k} \frac{N_{Freq}}{N_{intf} P_{A_k} N_{CH}} \\ &= (K+1) \frac{N_{Freq}}{N_{intf} \ N_{CH}}, \end{aligned} \tag{14}$$

where N_{intf} is the bandwidth reuse measure, and N_{Freq} is the number of frequencies available for simultaneous cluster head transmissions. Following Theorem 1, for equidistant hops with length R_c, the overall average per node throughput is expressed as

$$\bar{T} = \bar{P}_t \exp\left\{-\kappa N_{hop} R_c^\beta\right\}, \tag{15}$$

where N_{hop} is the average number of hops from a CH to its corresponding sink in each cell.

C. Multihop Multipath Routing Case

In the previous subsections, 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 $P_{i,l}$ 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:*

$$\begin{aligned} T_{i,k} &= \sum_{l=1}^{N} \sum_{p=1}^{P_{i,l}} T(i | N_i^k = l, \mathcal{P}_i^k = p) \Pr\{\mathcal{P}_i^k = p | N_i^k = l\} \\ &\quad \times \Pr\{N_i^k = l\}. \end{aligned} \tag{16}$$

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 for diversity, the utilized scheduling protocol, and hence $P(t_i^k = 1)$, could be different than that in the single routing path case. As a result, the average per node throughput varies with the diversity technique and the scheduling protocol adopted.

D. Total Network Throughput

The *network throughput*, Υ, is defined as the average number of packets received successfully from all clusters per

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSIPN.2016.2601021, IEEE Transactions on Signal and Information Processing over Networks

unit time.

Let $\mathcal{N}^k$ 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:

$$\begin{aligned}\Upsilon &= \sum_{k=0}^{K}\sum_{i\in\mathcal{N}^k} T_{i,k} \\ &= \sum_{k=0}^{K}\sum_{i\in\mathcal{N}^k}\sum_{l=1}^{N}\sum_{p=1}^{\mathcal{P}_{i,l}} T(i|N_i^k=l,\mathcal{P}_i^k=p) \\ &\qquad \times \Pr\{\mathcal{P}_i^k=p|N_i^k=l\}\Pr\{N_i^k=l\} \\ &= \sum_{k=0}^{K}\sum_{i\in\mathcal{N}^k}\sum_{l=1}^{N}\sum_{p=1}^{\mathcal{P}_{i,l}} p_i^k(p)\exp\left\{-\kappa\sum_{h=1}^{l}\left[L_{i_h^k,i_{h-1}^k}(p)\right]^{\beta}\right\} \\ &\qquad \times \Pr\{\mathcal{P}_i^k=p|N_i^k=l\}\Pr\{N_i^k=l\}, \qquad (17)\end{aligned}$$

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 $p_i^k(p)$ is the transmission probability of CH i along path p to sink k.

IV. System Stability and Delay Analysis

In this section, we analyze the stability and delay of MC-WSN by exploiting tools in queuing theory. After introducing the independence assumption and modeling theorems, we establish the queuing model of the CHs, and then perform the stability and delay analysis.

A. Queue Independence Assumption and Modeling Theorems

The difficulty in the system stability and delay analysis in communication networks is mainly attributed to the dependency between different queues along the routing path of a packet. Let the arrival time of packet j at a queue be T_j. Then, the *inter-arrival time* between packets j and $j+1$ is $A_j = T_{j+1} - T_j$. The *service time* at a node is generally defined as the duration between the time the packet is at the head of the node's queue until it is successfully transmitted. In other words, the service time equals to the packet length divided by the service rate.

1) Kleinrock Independence Assumption: In networks of tandem queues, there is generally a correlation between the inter-arrival times and the packet lengths/service times at the intermediate queues [24]. For example, if the packets retain their lengths when they are forwarded at different hops, considering that the link rates are fixed, then we have: (i) dependency between the inter-arrival times and service times at each of the intermediate queues; (ii) dependency between service times at different queues. Due to these dependencies, network analysis becomes highly complicated and intractable.

However, it was observed that when the network is densely connected with moderate to heavy traffic loads, these dependencies can be removed [25]. In other words, the dependencies between the inter-arrival times and service times can largely be eliminated by merging multiple packet streams on each link [24]. This is known as the *Kleinrock independence assumption*. *More specifically, in a densely connected network with moderate to heavy traffic loads, if we have Poisson arrival processes at the entry points of the network, and exponentially distributed service times at each link, then the multiplexing of the independent Poisson packet streams at every node has the effect similar to restoring the independence between the inter-arrival times and service times* [24].

The underlying argument is that: if packets received by a node from different sources are ordered in the queue by the order they arrive in a first-come first-served manner, the resulted queues through the packet multiplexing/merging process become independent. The idea here is similar to the interleaving process in communication systems, which randomizes consecutive symbols and validates the independence assumption among all the symbols.

The independence assumption was verified through experiments in [24] using different network topologies (star, diamond, and k-connect networks) under uniform and non-uniform traffic. It was shown that *the independence assumption provides a valid model for network analysis*. It should be noted that, having an exponentially distributed packet lengths and deterministic service process is equivalent to having fixed packet lengths and Poisson service process. Both cases will result in an exponentially distributed service time. The independence assumption allows us to treat the packets at each node in the network independently as an M/M/1 queue [24], and hence enables tractable network analysis.

2) Burke's Theorem and Little's Theorem: Next, we introduce two important queue modeling and analyzing theorems that will be used in our analysis in the following subsections. The first one is the *Burke's theorem* [25], which describes the relationship between the arrival flow and the service flow.

Burke's theorem*: *Consider an M/M/1, M/M/m, or M/M/∞ system with Poisson arrival process of rate λ_x, then the departure process is Poisson with rate λ_x.

The second one is the well-known *Little's theorem* [25], which formulates the average delay per packet as a function of the average arrival rate and the number of packets in the system.

Little's theorem*: *Let the steady state average number of packets in a system be N_x and the average packet arrival rate be λ_x, then the average delay per packet in the system $D_x = \frac{N_x}{\lambda_x}$.

In the next subsection, we characterize the queuing model of cluster heads in MC-WSN.

B. Queuing Model Characterization for MC-WSN

1) Queuing Model for the Arrival and Service Processes: In this subsection, we provide the queuing model for each individual CHs in MC-WSN, and show that the *Kleinrock independence assumption* provides an accurate model for stability and delay analysis of the MC-WSN network. More specifically, we have the following result:

Theorem 3. *(i) The service process of each queue can be modeled as a Poisson process and is independent from node to node. (ii) The arrival process at each queue can be modeled as a Poisson process.*

Proof. (i) Service Process: In Section III, we showed that the SNR can be modeled as an exponentially distributed random variable. *Due to the exponentially distributed SNR*, different links in the MC-WSN multihop transmissions have different service times that are independent from link to link. Recall that the throughput from node i to j, $T_{i,j}$, is defined as the average number of packets per slot that are initiated by node i and successfully delivered to j. It follows that, the number of packets successfully transmitted from i to j in c slots can be modeled as a Binomial random variable with parameters c and $T_{i,j}$ [33]. According to the *law of small numbers*, when large time interval is considered, i.e., $c \to \infty$, the Binomial distribution with parameters c and $T_{i,j}$ converges to a Poisson distribution with parameter $S = cT_{i,j}$ [33]–[35].

(ii) Arrival process: All the CHs can be divided into two groups: (a) CHs that only transmit packets generated from their own clusters. (b) CHs that serve as relays for other CHs, and hence transmit their generated traffic and also the relay traffic. Without loss of generality, consider two CHs i and j, where CH i receives data from its cluster members (sensors) only, while CH j receives data from its cluster members as well as from CH i. Note that in general the aggregation of several independent and identically distributed traffic can be accurately approximated as a Poisson process ([25], p. 165). Hence, the arrival process of packets from sensors to their corresponding CHs can be modeled as a Poisson process. That is, CH i has a Poisson arrival process.

Next, we will show that CH j has an overall Poisson arrival process as well. Since the service process from each CH is Poisson, therefore the packets at CH i is an M/M/1 queue. It follows from the *Burke's theorem* that the departures process of CH i is Poisson distributed. The Poisson departures from CH i arrive at CH j and are merged with data from sensors in cluster j, which is also Poisson. Since the merging of independent Poisson processes of rates $\{\lambda_1, ..., \lambda_n\}$ is a Poisson process of rate $\lambda_t = \sum_i^n \lambda_i$ [25], then the overall arrival process at CH j has a Poisson distribution. This proof can be directly extended to CHs that serve as a relay for more than one CH. □

Based on the discussions above, the packets at each CH in the network can be modeled as an independent M/M/1 queue. Our stability and delay analysis are based on this model.

2) Calculation of Arrival and Service Rates: Here, we calculate the arrival and service rates of CHs by considering different traffic loads at the CHs in the network. To do this, we first group the CHs based on their locations and the number of hops to their corresponding sink (either the CCH or an RCH).

- For the CCH: Due to the uniformity of the MC-WSN structure achieved by the MA, it is reasonable to assume that all CHs at the same hop level from the CCH carry approximately the same amount of traffic. Hence, for delay analysis, we do not distinguish between nodes within the same hop level from the CCH.
- For the RCHs: The traffic around the RCH could be different due to the unequal areas. More specifically, within a particular RCH coverage area, illustrated in Figure 2, the outer region, where $x > R_t$, and the inner region, where $R_o < x \leq R_t$, have different traffic loads. This is because the area of the outer region is larger than that of the inner region, which corresponds to larger number of hops and more CHs in the outer region. Therefore, when analyzing the performance of the CHs around the RCH, we identify the nodes by their hop level as well as their region from the RCH (inner or outer region). Nodes within the same hop level of a particular region from a RCH are not distinguished.

From the discussions above, without loss of generality, we define the following:

- $g^O_{h,k}$ is the group of nodes in the hth hop level from sink k and in the outer region. Similarly, $g^I_{h,k}$ is the group of nodes in the hth hop level from sink k and in the inner region. The superscript O and I are omitted when referring to the CCH.
- $\lambda^O_{i,h,k}$ and $\lambda^I_{i,h,k}$ are the total arrival rates at CH $i \in g^O_{h,k}$ and $i \in g^I_{h,k}$, respectively.
- $s^O_{i,h,k}$ and $s^I_{i,h,k}$ are the service rates at CH $i \in g^O_{h,k}$ and $i \in g^I_{h,k}$, respectively.

Take a CH at the hth hop from the outer region of sink k as an example. Based on the independence assumption, it can be modeled as an M/M/1 queue with total arrival rate $\lambda^O_{i,h,k}$ and service rate $s^O_{i,h,k}$.

The total arrival rate at a CH is the sum of the arrival rate of packets from its own cluster members and the arrival rate of packets forwarded from other cluster heads to be delivered to the nearest sink. We refer to the former as the "*generated arrival rate*", denoted by $\tilde{\lambda}_{g,i}$, while the latter is referred to as "*forwarded arrivals rate*", denoted by $\tilde{\lambda}^O_{f,i,k}$ or $\tilde{\lambda}^I_{f,i,k}$, depending on where the CH resides. Following our discussions in the previous subsection, we assume that the traffic generated from each cluster in the network follows a Poisson process with equal rates, and is independent of the hop level or the location in the network. That is, $\tilde{\lambda}_{g,i} = \lambda \; \forall i$. In the following, we consider the analysis of CHs in the outer regions of the sinks (RCHs). The analysis of CHs in the inner regions as well as those within the coverage area of the CCH can be performed in a similar manner.

We characterize the forwarded traffic to CH $i \in g^O_{h,k}$ based on the *Burke's theorem*. Let $N^O_{f,h,k}$ be the number of cluster heads that forward their data through CH $i \in g^O_{h,k}$ on their route to sink k. It follows that the rate of the forwarded traffic to CH $i \in g^O_{h,k}$ is: $\tilde{\lambda}^O_{f,i,k} = N^O_{f,h,k}\lambda$, Hence, the total arrival rate to CH i is:

$$\begin{aligned} \lambda^O_{i,h,k} &= \lambda_{g,i} + \tilde{\lambda}^O_{f,i,k} \\ &= \left(1 + N^O_{f,h,k}\right)\lambda, \quad i \in g^O_{h,k},\; h \in \{1, ..., N\} \end{aligned} \tag{18}$$

where N is the largest number of hops from a CH to its sink along any routing path.

In the following, we model the service rate of the CHs. Let T_{slot} be the slot duration in seconds, then the average service rate in packets per second from node i to j is $\frac{T_{i,j}}{T_{slot}}$, where $T_{i,j}$ is the throughput from node i to node j. It follows from the analysis in Section III, that the throughput of a direct one-hop transmission from a CH at the hth hop to

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSIPN.2016.2601021, IEEE Transactions on Signal and Information Processing over Networks

a CH at the $(h-1)$th hop from the outer region of sink k is obtained as: $Pr\{t^{k,O}_{i_h,j_{h-1}}=1\}Pr\{SNR^{k,O}_{i_h,j_{h-1}}>\gamma\}$, where $Pr\{t^{k,O}_{i_h,j_{h-1}}=1\}$ is the probability that CH $i\in g^O_{h,k}$ is scheduled to transmit a packet to CH $j\in g^O_{h-1,k}$, and $Pr\{SNR^{k,O}_{i_h,j_{h-1}}>\gamma\}$ is the probability of successful reception of a packet at hop level $h-1$. Hence, the corresponding average service rate is expressed as

$$s^O_{i,h,k}=\frac{1}{T_{slot}}Pr\{t^{k,O}_{i_h,j_{h-1}}=1\}Pr\{SNR^{k,O}_{i_h,j_{h-1}}>\gamma\}. \quad (19)$$

Following *Theorem 1*, under exponentially distributed SNR, we have:

$$s^O_{i,h,k}=\frac{1}{T_{slot}}Pr\{t^{k,O}_{i_h,j_{h-1}}=1\}\exp\left\{-\frac{\gamma}{\overline{SNR}_h}\right\}, \quad (20)$$

where $\overline{SNR}_h=\frac{\bar{P}L^{-\beta}_{i_h,j_{h-1}}}{N_o}$. For equidistant hops, we have $\overline{SNR}_h=SNR,\ \forall h$.

C. Stability Analysis

Assuming that the arrival and departure processes are stationary, then for a system to be stable, the service rate must be larger than the arrival rate at each queue [13], [36]–[39]. That is, for $i\in g^O_{h,k}$ and $\forall h,k$ we must have:

$$s^O_{i,h,k}>\lambda^O_{i,h,k} \quad\Rightarrow\quad s^O_{i,h,k}>\left(1+N^O_{f,h,k}\right)\lambda. \quad (21)$$

The stability condition would impose a requirement on how often a node is scheduled to transmit. Intuitively, nodes closer to the sink should be scheduled more often than other nodes, due to the larger amount of traffic they relay to the sink. Alternatively, for a particular scheduling, the stability will impose an upper bound on the rate at which traffic is generated λ. Following (20) - (21), we have the following result for any CH $i\in g^O_{h,k}$. Similar results can be obtained for nodes in other regions.

Proposition 2. *(Node stability analysis) For the node buffer to be stable, a CH $i\in g^O_{h,k}$ should be scheduled to transmit to the nearest CH $j\in g^O_{h-1,k}$ with a probability*

$$Pr\{t^{k,O}_{i_h,j_{h-1}}=1\}>\frac{T_{slot}\left(1+N^O_{f,h,k}\right)\lambda}{\exp\left\{-\frac{\gamma}{SNR}\right\}}, \quad \forall i,k. \quad (22)$$

Corollary 1. *For a particular scheduling protocol, to ensure node stability for any CH $i\in g^O_{h,k}$, the arrival rate of the self-generating traffic of each cluster must satisfy:*

$$\lambda<\arg_{k,h}min\ Pr\{t^{k,O}_{i_h,j_{h-1}}=1\}\frac{\exp\left\{-\frac{\gamma}{SNR}\right\}}{T_{slot}\left(1+N^O_{f,h,k}\right)}, \quad \forall i. \quad (23)$$

Remark 3. *As can be seen, the system stability is guaranteed as long as the transmission probability is above a certain threshold. This condition, in turn, can be fulfilled by providing sufficient channels and/or utilizing signal processing techniques for simultaneous transmissions [40]. Note that the stability condition can also be mapped to a lower bound on the transmission power at each CH. However, this is not recommended due to two reasons: (i) The transmission power is generally limited. (ii) Increasing the power would result in increased interference, which could reduce the frequency reuse efficiency.*

Recall Lemma 1 in Section III that states that the probability at which a CH is scheduled to transmits its *own* traffic to sink k is lower bounded by $P\{t^k_i=1\}\geq\frac{N_{Freq}}{N_{intf}\ n_k}\ \forall k,i$. In other words, there is a scheduled time of length equal to or less than $\frac{N_{intf}\ n_k}{N_{Freq}}$ slots, where each CH can send *one* of its own generated packets to sink k. At each hop, a single CH transmits its own traffic as well as the relayed traffic from other CHs. That is, it transmits in a total of $\left(1+N^O_{f,h,k}\right)$ slots in a single scheduling period. Thus, we have:

$$Pr\{t^{k,O}_{i_h,j_{h-1}}=1\}\geq\frac{\left(1+N^O_{f,h,k}\right)N_{Freq}}{N_{intf}\ n_k}, \quad i\in g^O_{h,k},\ j\in g^O_{h-1,k}. \quad (24)$$

When the lower bound on the transmission probability in (24) is higher than that in (22), then the stability is guaranteed through proper scheduling. We have the following result:

Corollary 2. *In the worst case when the scheduling protocol satisfies (24) with equality, then a necessary condition to ensure stability is $\frac{(1+N^O_{f,h,k})N_{Freq}}{N_{intf}\ n_k}>\frac{T_{slot}(1+N^O_{f,h,k})\lambda}{\exp\{-\frac{\gamma}{SNR}\}}$. It follows that for system stability, the number of clusters within the service area of sink k must be bounded as follows:*

$$n_k<\frac{N_{Freq}\exp\left\{-\frac{\gamma}{SNR}\right\}}{N_{intf}\lambda T_{slot}}, \quad \forall k. \quad (25)$$

Remark 4. *Based on N_{Freq}, the arrival rate λ, and the average link throughput, the number of RCHs K can be chosen such that (25) is satisfied.*

D. Delay Analysis

Based on the *Kleinrock independence assumption*, the traffic at each CH can be modeled as an M/M/1 queue whose rates are obtained as illustrated in the previous subsections. We define the utilization factor of CH $i\in g^O_{h,k}$ as:

$$\rho^O_{i,h,k}=\frac{\lambda^O_{i,h,k}}{s^O_{i,h,k}}, \quad (26)$$

where $\lambda^O_{i,h,k}$ and $s^O_{i,h,k}$ are the arrival rate and the service rate of CH $i\in g^O_{h,k}$. Hence, the expected number of packets in the queue at CH i is $\mathcal{N}^O_{i,h,k}=\frac{\rho^O_{i,h,k}}{1-\rho^O_{i,h,k}}=\frac{\lambda^O_{i,h,k}}{s^O_{i,h,k}-\lambda^O_{i,h,k}}$ [25]. The average delay per packet (in seconds) along the queue at CH $i\in g^O_{h,k}$ is obtained using *Little's theorem* [25] as:

$$D^O_{i,h,k}=\frac{\mathcal{N}^O_{i,h,k}}{\lambda^O_{i,h,k}}=\frac{1}{s^O_{i,h,k}-\lambda^O_{i,h,k}}. \quad (27)$$

The delay in a transmission from a CH to a sink is the sum of the delays encountered at all intermediate hops along the route to the sink. Let $\bar{D}(i\in g^O_{h,k})$ be the average delay per packet of node $i\in g^O_{h,k}$, thus we have

$$\bar{D}(i\in g^O_{h,k})=\sum_{\substack{j=1\\ x\in g^O_{j,k}}}^{h}D^O_{x,j,k}. \quad (28)$$

Delay analysis for CHs in other regions can be performed similarly.

Let $\mathbb{N}^O_{h,k}$ be the number of nodes at the hth hop from RCH k in the outer region, and $\mathbb{N}^I_{h,k}$ are those in the inner region. Also, let $\mathbb{N}_{h,0}$ be the number of nodes at the hth hop level from the CCH ($k = 0$). Define $\mathbb{N}^O_k$ and $\mathbb{N}^I_k$ as the maximum number of hops to RCH k from the outer and inner regions, respectively, while $\mathbb{N}_0$ is the maximum number of hops to the CCH from a CH in the region $x < R_o$. Assuming that all CHs have data to transmit, we get the overall average delay in the cell by summing the delay encountered by a transmission from each CH to its nearest sink, then dividing by the number of CHs in the cell. In summary, we have the following proposition:

Proposition 3. *(Single-path case) The average delay of a packet in the network to reach its corresponding stationary sink (CCH/RCH) along a predefined single routing path can be expressed as:*

$$\begin{aligned} \bar{\mathbb{D}} \;=\; & \Bigg[K \left(\sum_{h=1}^{\mathbb{N}^O_k} \mathbb{N}^O_{h,k} \bar{D}(i \in g^O_{h,k}) + \sum_{h=1}^{\mathbb{N}^I_k} \mathbb{N}^I_{h,k} \bar{D}(i \in g^I_{h,k}) \right) \\ & + \sum_{h=1}^{\mathbb{N}_0} \mathbb{N}_{h,0} \bar{D}(i \in g_{h,k}) \Bigg] \frac{1}{N_{CH}}. \end{aligned} \tag{29}$$

Note that due to the symmetry of the architecture, we get the delay of traffic around a single RCH, multiply by K, then add it to the delay of packets in the CCH region; the result is then divided by the number of CHs in the network to obtain the overall average delay per packet.

Under routing diversity, the result for the single path case can be extended to the multipath case as follows:

Proposition 4. (Multipath case) 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 $P_{i,l}$ possible l-hop paths from CH i to sink k. Let $\bar{D}_{i,k}(N^k_i = l, \mathcal{P}^k_i = p)$ be the average delay along one of the l-hop paths from source i to sink k assuming the path $\mathcal{P}^k_i = p$, then the overall average delay of node i's packet can be calculated as:

$$\begin{aligned} \bar{D}_{i,k} \;=\; & \sum_{l=1}^{N} \sum_{p=1}^{P_{i,l}} \bar{D}_{i,k}(N^k_i = l, \mathcal{P}^k_i = p) \\ & \times \Pr\{\mathcal{P}^k_i = p | N^k_i = l\} \Pr\{N^k_i = l\}. \end{aligned} \tag{30}$$

Let $\mathcal{N}^k$ be the set of CHs that transmit to sink k, then the overall average per packet delay in the network can be expressed as:

$$\bar{\mathbb{D}} = \frac{1}{N_{CH}} \sum_{k=0}^{K} \sum_{i \in \mathcal{N}^k} \bar{D}_{i,k}. \tag{31}$$

V. Energy Efficiency

Energy consumption is a primary concern in wireless sensor networks due to the limited power resource of the individual sensors. As will be shown in this section, MC-WSN provides an energy efficient architecture. 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 [41], [42]. 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, ϵ_{pa} is the energy consumed by the power amplifier, β 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:

$$E_{SN,M} = E_{tx} + \epsilon_{pa} r_c^\beta \quad (J/bit). \tag{32}$$

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]:

$$E_{SN,S} = E_{tx} + \epsilon_{pa} H_S^\beta + E_{rx} \pi r^2 \frac{n}{A_T}, \tag{33}$$

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 (33) compared to (32). That is, even if $r_c^\beta = H_S^\beta$, the energy consumption in SENMA is higher than that in MC-WSN. This will be further illustrated in Section VI.

Remark 5. *It should also be noted that in MC-WSN, the MA can recharge or replace the low power nodes, hence largely relaxes the power limitation and prolongs the lifetime of the network.*

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 hops on the throughput performance. Then, we obtain the bound on the arrival rate to guarantee network stability. Finally, under stable system conditions, we evaluate the delay and energy efficiency performance. The performance of MC-WSN is compared to that of SENMA.

Recall that in MC-WSN we assume that: (i) 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. That is, we have at least $K + N_{Freq} + 2$ channels; (ii) CCH and RCH can communicate directly with MA; (iii) sensors are not involved in the inter-cluster routing, and multihop transmissions are made through CHs; (iv) throughput calculations are based

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on multihop transmission between CHs; (v) unless otherwise stated, TDMA is used for scheduling multihop transmissions when $N_{Freq} = 1$ and TDMA/FDMA is used when $N_{freq} > 1$.

In the simulations, unless otherwise stated, we use the following parameters: the communication range of the cluster heads is $R_c = 30$m and that of sensors is $r_c = 15$m, the optimal values for R_o and R_t are set according to *Proposition 1*, the path loss exponent is $\beta = 2$, the SNR threshold is $\gamma = 5$dB, the bandwidth reuse measure is $N_{intf} = 2$, the cell radius is $d = 200$m, the number of cluster heads is $N_{CH} = 200$, the number of RCHs is $K = 6$, and the number of frequencies available for simultaneous transmissions is $N_{Freq} = 1$ or 4.

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 $T_{slot} = 25.6$ms. Note that the same slot duration will be needed if the packet size is 128 bytes, and the data rate 40kbps.

Example 1: Throughput Calculations In this example, first, the per node throughput is calculated for a multihop transmission, and the effect of the number of hops is illustrated. The results are shown in Figures 3 and 4, where we assume a normalized source-destination distance and normalized per hop distance, respectively. It can be seen that: (i) *if the source-destination distance is fixed, under a particular per node SNR, there exists an optimal number of hops for throughput maximization as shown in Figure 3*; (ii) *if the SNR is fixed and the hops are equidistant, then the throughput decreases as the source-destination distance or the number of hops increases as shown in Figure 4*. In this paper, since the per hop distance is assumed fixed, our objective is to minimize the number of hops in the topology design, and hence improve the network performance.

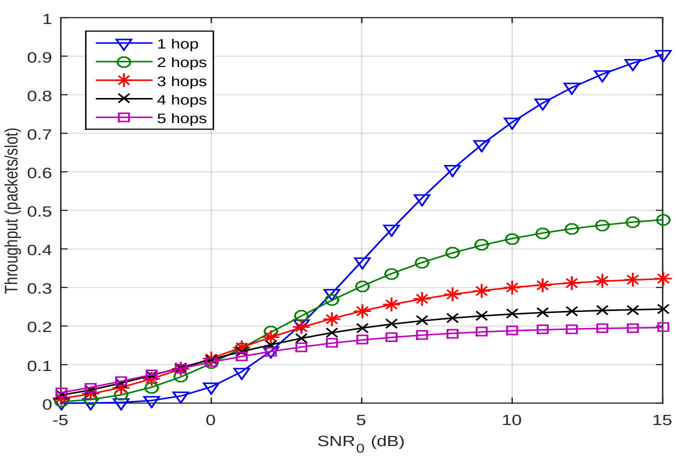

Fig. 3. Single link throughput versus $SNR_0 = \frac{\bar{P}}{N_o}$, the mean SNR for a unit transmission distance. Here, the source-destination distance is fixed, and no bandwidth reuse is involved in different hops of a multihop transmission.

Next, we compare the throughput performance of MC-WSN to that of SENMA. 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. In SENMA, the transmission probability of any sensor can be evaluated as:

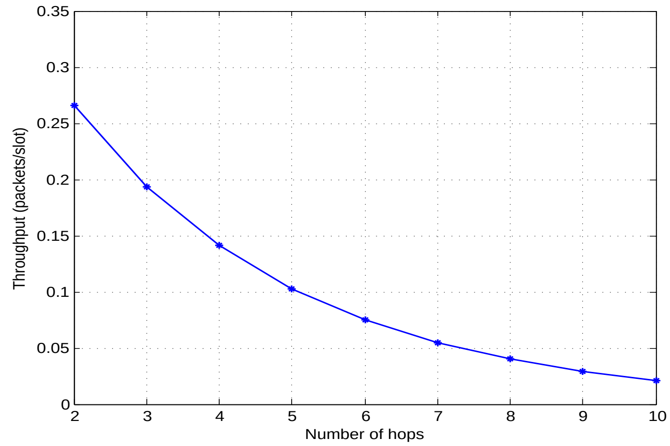

Fig. 4. Throughput versus the number of hops when the per hop distance is fixed, $SNR = 10$dB, $\gamma = 5$dB, $P(t_i^k = 1) = 1/N_{intf}$.

$P(t_{SENMA} = 1) = \frac{T_{slot}}{\frac{L_{MA}}{V_{MA}} + nT_{slot}}$, 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. 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.

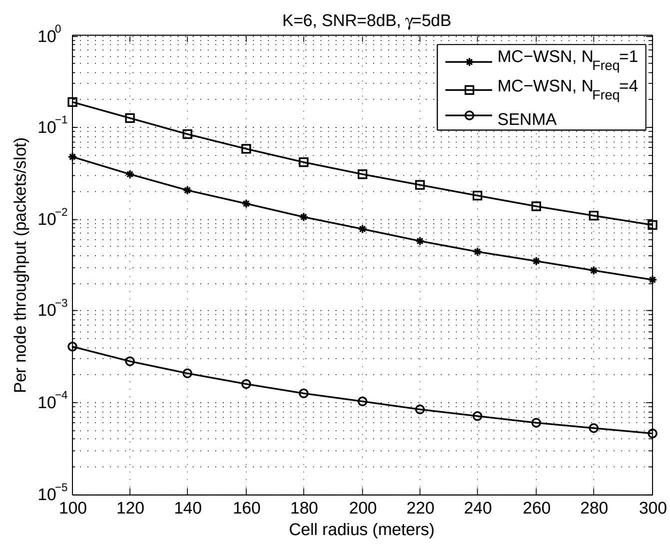

Fig. 5. Average per node throughput in packets per slot vs. the cell radius for both MC-WSN and SENMA. Here, $K = 6$, $V_{MA} = 30$m/s, $\rho_{SN} = \frac{n}{\pi d^2} = 0.0283$, $\rho_{CH} = \frac{N_{CH}}{\pi d^2} = 0.0014$, $SNR = 8$dB.

Example 2: 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 [43]. In the network setup, we deploy CHs in layers with respect to the CCH and the interval between neighboring layers is R_c. The CHs in each layer are uniformly distributed on a circle according to density ρ_{CH}. We then

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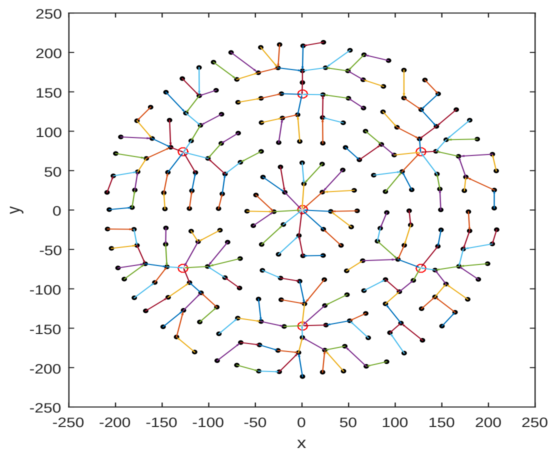

Fig. 6. Network deployment and routing paths.

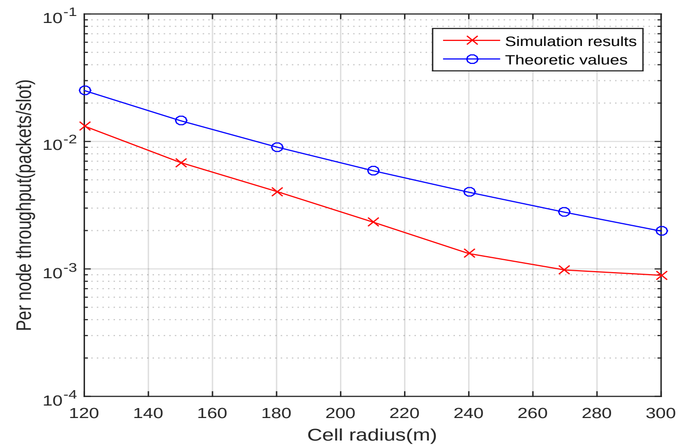

Fig. 7. Throughput under non-ideal network settings: comparison of the theoretical and simulation results.

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 $d = 200$m.

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 (collision free) and simulation results is shown in the Figure 7.

Example 3: Maximum packet generation rate for network stability In this example, we evaluate the upper bound on the packet generation rate λ for $N_{Freq} = 1, 4$, and plot it versus the SNR. The upper bound on λ that guarantees stability is shown in Figure 8. Here, we assume (24) holds with equality. As can be seen, higher data generation rates can be supported with higher SNR values. Also, as N_{Freq} increases, even higher rates can be tolerated at the same SNR level.

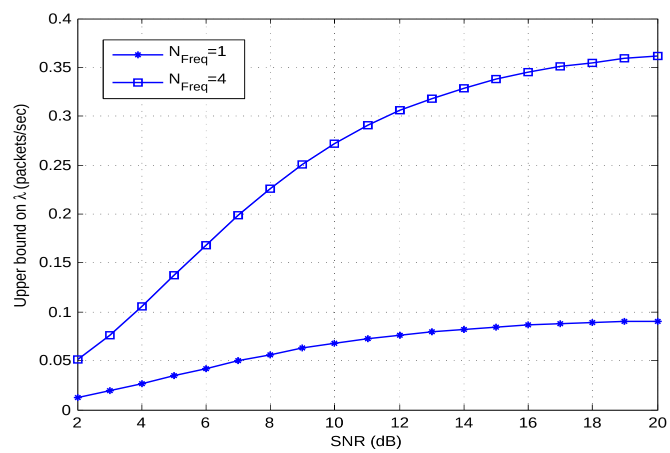

Fig. 8. Upper bound on packet generation rate in each cluster (λ) for MC-WSN when, $d = 200$m, $N_{CH} = 200$, and $K = 6$.

Example 4: Delay comparison In this example, we obtain the average delay per packet of MC-WSN, and compare it to that of SENMA. Denote the upper bound on λ as λ_{UB}, and set $\lambda = 0.9\lambda_{UB}$. The transmission probability is obtained from (24). For MC-WSN, we mainly consider the delay in the transmissions from the source cluster head to its corresponding sink (CCH/RCH). The delay from a sensor to its CH and from the CCH/RCH to the MA are negligible when compared to the queuing and transmission delays of the intermediate multihop transmissions. For SENMA, the delay in packet transmission is mainly dominated by the waiting time until the MA visits the source sensor; a node can be anywhere along the trajectory, hence the average delay for a node to transmit to the MA is $D_S = \frac{L_{MA}}{2V_{MA}}$, where L_{MA} is the length of the MA's trajectory and V_{MA} is the speed of the MA. Here, we assume $V_{MA} =$ 30m/s. In the delay calculations for SENMA, we ignore the transmission time of signals from the sensors to the MA, and

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the transmission time of the MA's beacon signal that notifies the sensors to transmit, as well as the waiting time of the MA at each location for data collection.

The delay versus the SNR is shown in Figure 9. It is clear that MC-WSN provides orders of magnitude lower delay than that of SENMA, and even lower delays are possible when larger number of orthogonal frequencies, N_{Freq}, is available.

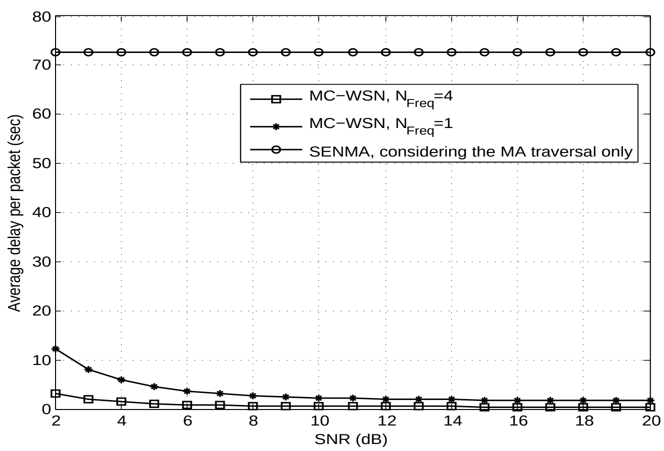

Fig. 9. Average delay of MC-WSN and SENMA vs. received SNR. Here, $d = 200$m, $N_{CH} = 200$, $K = 6$, and $V_{MA} = 30$m/s.

Example 5: Energy efficiency comparisons In this example, we compare the average energy dissipation of individual sensors in both MC-WSN and SENMA. We focus on the individual sensors because they have the most limited resources. We calculate the energy dissipation for a sensor to report a single bit in MC-WSN and SENMA using (32) and (33), respectively. The result is shown in Figure 10. Here, for SENMA, we assume the access point traverses the network at a height H_S broadcasting beacon signals at random locations. The coverage area of the access point is modeled as a circle of radius r. For comparison purpose, we set r in SENMA to be the same as the cluster radius in MC-WSN, i.e., $r = r_c$. Note that the MA can tune r by adjusting the power of the beacon signal.

It can be seen from Figure 10 that MC-WSN is significantly more energy-efficient than SENMA, and the energy efficiency gains increase as the density of the sensors increases. The reason is that in SENMA, each sensor must first receive a beacon signal from the MA in order to report its data. All sensors within the coverage area of the MA receive the beacon signal, and only one sensor responds each time [1]. The energy dissipation during the multiple beacon reception process contributes significantly to the overall energy consumption in SENMA.

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, stability, delay and energy efficiency. It was shown that with active network deployment and hop number control, MC-WSN achieves much higher throughput and considerably lower delay and energy consumption over the conventional SENMA. Moreover, our analysis also indicated that with hop number control, network analysis does become more tractable.

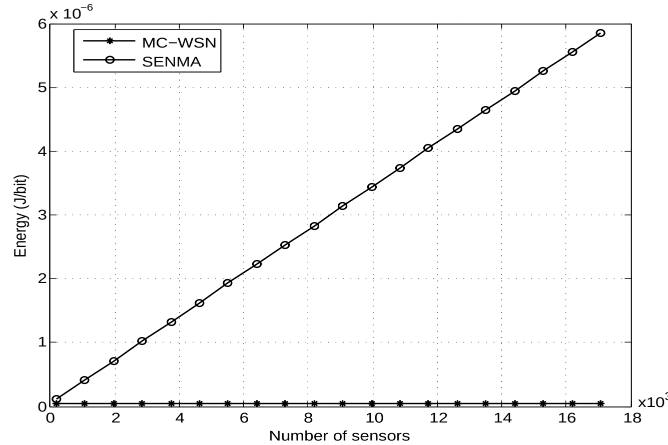

Fig. 10. The energy dissipation (J/bit) vs. the number of SNs in the MC-WSN and SENMA networks, when $r_c = r = 15$m, $H_S = 10$m, $\beta = 2$, $E_{tx} = E_{rx} = 50$ nJ/bit, $\epsilon = 10$ pJ/bit/m^2, and $d = 200$m.

Appendix A
Topology Design for $K = 1, 2$

For the special cases of $K = 1, 2$, the proposed topology may indeed cause some detour for the CHs in some regions. In these case, an alternative network deployment can be applied: instead of placing the CCH at the center of the cell, we evenly distribute the CCH and the K RCHs on the ring of radius R_t, and all the CHs are routed to their nearest CCH/RCHs. To obtain the optimal value of R_t, we minimize the average squared distance from a generic node to its sink, which is

$$\begin{aligned}&\min_{R_t}\ 2(K+1)\cdot\int_0^{\frac{\pi}{K+1}}\int_0^d [(x\cdot\cos\theta - R_t)^2 + (x\cdot\cos\theta)^2]\\&\qquad\qquad f_X(x) f_\theta(\theta)\mathrm{d}x\mathrm{d}\theta\\&=\min_{R_t}\ c\cdot[\frac{d^4\pi}{2(K+1)} - \frac{4}{3}R_t d^3 \sin\frac{\pi}{K+1} + \frac{R_t^2 d^2\pi}{K+1}],\quad \text{(A-1)}\end{aligned}$$

where c is a constant irrelevant to R_t, x is the distance of a node from the center of the cell, and $f_X(x)$ is the PDF of x. Differentiate (A-1) w.r.t. R_t, the optimal R_t that can minimize (A-1) is

$$R_t^* = \frac{2d}{3\pi}\cdot(K+1)\cdot\sin\frac{\pi}{K+1}. \quad \text{(A-2)}$$

Then maximal hop number is

$$N = 2 + \left\lceil \frac{1}{R_c}\max\left\{R_t, \sqrt{d^2 - 2dR_t\cos(\frac{\pi}{K}) + R_t^2}\right\}\right\rceil, \quad \text{(A-3)}$$

and other performance metrics can be derived accordingly.

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