

Chain-Type Wireless Sensor Network for Monitoring Long Range Infrastructures: Architecture and Protocols*

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We present in this paper an investigation of a special class of wireless sensor networks for monitoring critical infrastructures that may extend for hundreds of miles in distances. Such networks are fundamentally different from traditional sensor networks in that the sensor nodes in this class of networks are deployed along narrowly elongated geographical areas and form a chain-type topology. Based on careful analysis of existing sensor network architectures, we first demonstrate the need to develop new architecture and networking protocols to match the unique topology of chain-type sensor networks. We then propose hierarchical network architecture that consists of clusters of sensor nodes to enable the chain-type sensor networks to be scalable to cover typically long range infrastructures with tolerable delay in network-wide data collection. To maintain energy efficient operations and maximize the lifetime for such a chain-type sensor network, we devise a smart strategy for the deployment of cluster heads. Protocols for network initialization and seamless operations of the chain-type sensor networks are also developed to match the proposed hierarchical architecture and cluster head deployment strategy. Simulations have been carried out to verify the performance of the hierarchical architecture, the smart node deployment strategy, and the corresponding network initialization and operation protocols.

Keywords Wireless Sensor Networks; Chain-Type Topology; Infrastructure Monitoring; Smart Cluster Head Deployment

1. Introduction

Over the last few years, significant research and tremendous efforts have been devoted to investigating various challenging technical issues in wireless sensor networks, including low-power signal processing [1], power-aware media access control [2–4], energy-aware data aggregation and routing [5–14], topology management [15,16], localization [17], synchronization [18,19], and collaborative signal and information processing [20–23]. The central theme shared by these techniques is the energy efficiency issue for different algorithms in order to implement operational functions of wireless sensor networks,

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including sensing, signal processing, data routing and networking, radio communication, and power management, under the severe power supply constraint.

Existing wireless sensor networks and systems usually assume that sensor nodes are deployed in a distributive fashion within a relatively concentrated two dimensional or even three dimensional regions of interest. Some of them further assume that each node in a sensor network has the ability to transmit data to any other sensor node or directly to the base station [9, 10]. These sensor networks are indeed applicable to numerous applications to extend our ability to monitor and control the physical world, including biological and environmental monitoring tasks, ranging from marine to soil and atmospheric context [24–26], and defense and homeland security applications, ranging from target detection and classification, to object tracking and intrusion detection [20–23, 27–29].

However, these existing schemes cannot be effectively applied to a class of critical sensor network applications in which the sensor nodes are strategically deployed with chain-type topology along a relatively long range of distance. This class of applications is often limited by their natural formation of landscape or manmade infrastructures of long ranges, such as rivers, coastal lines, highways, and national land borders. The geographical nature of these premises demands that the deployment of the sensor nodes be restricted to the long stretch of narrow and elongated spreading.

Potential applications of chain-type wireless sensor networks are numerous. One prime example of such sensor networks will be the water quality and the resource monitoring system that can be deliberately deployed along major rivers. This type of wireless sensor networks shall consist of biological or chemical sensors that can detect certain water contaminations, e.g., excess antibiotics discharge from the digestive systems of animals and eventually into ground and surface water. The success of such sensor networks will prevent the contaminated water from entering the nation's water supply system which in turn may pose unknown human health risks of drinking contaminated water. Other examples include hurricane wind monitoring along coastal areas, traffic and transportation monitoring along major highways and extended port areas, surveillance and monitoring of long land borders between countries, as well as monitoring of other critical infrastructure with elongated geographical areas that may extend tens to hundreds of miles in length.

1.1. Technical Challenges

It is true that the chain-type wireless sensor networks under consideration in this research share many inherent characteristics of general wireless sensor networks since such networks also consist of a large number of unattended sensor nodes in potentially harsh environments. The chain-type sensor networks also operate under severe resource constraints, including restricted energy supply, low bandwidth, scarce computational power, and limited communication capability.

However, their unique chain-type topology and their usually deliberate deployment at strategic locations along the infrastructure of interest make these networks much more restrictive in terms of inter node communication, sensor data aggregation, and seamless flow of sensing data and control commands. These additional restrictions pose a new set of technical challenges that are different from those in the existing sensor networks. In this research, we propose to tackle several key challenges that can significantly impact the overall performance of the chain-type sensor networks.

The first challenge such chain-type sensor networks will be facing is the development of scalable and energy efficient networking architecture that would enable the

sensor networks to maximize their lifetime while minimizing the overall deployment cost. We expect that two unique characteristics of chain-type sensor networks, namely,

- 1) linear manner deployment of sensor nodes, and
- 2) long distance stretching of network dimension, will significantly influence the design of the new architecture.

Furthermore, data delivery models of a particular application will also affect the overall architecture of the sensor network.

The second challenge for such chain-type sensor networks is to develop energy efficient communication protocols for the sensor nodes to communicate with each other and with the data sink of the wireless sensor network. Because of the unique chain-type topology, the radio communications between sensor nodes are limited by directional transmission along the path of chain-type sensor node distributions. These protocols will determine when the radio communications should be activated based on a minimum energy principle and how the sensor nodes should coordinate the data transmission within the local vicinity and with the remote data sink.

The third challenge for such chain-type sensor networks is to develop a MAC protocol to enable seamless communication among sensor nodes. Existing sensor network research usually assumes that sensor nodes are deployed in a distributive fashion within a relatively concentrated two-dimensional or even three-dimensional regions of interest. Some of them further assume that each node in a sensor network has the ability to transmit data to any other sensor node or directly to the base station [9,10]. Existing MAC protocols developed for wireless sensor networks are also based on these assumptions to design energy efficient MAC protocols for sensor data communications. Because of the unique chain-type topology, the radio communications between sensor nodes are limited by directional transmission along the path of chain-type sensor node distributions. The success of these MAC protocols will determine how seamlessly such a sensor network operates and how efficiently the chained sensor nodes will coordinate the data transmission within a cluster of sensor nodes and with the remote data sink.

2. Objectives and Overview of the Approach

The objective of this research is to develop novel architecture, node deployment strategy, and networking protocols for the special class of chain-type wireless sensor networks. We shall demonstrate the needs to develop new architecture and protocols to match the unique topology of chain-type wireless sensor networks because existing architecture and protocols become impractical and inefficient when applied to such chain-type network topology. To maintain energy efficient operations and to maximize the lifetime, we shall devise a novel strategy for the deployment of sensor nodes and for the design of network initialization and operation protocols. The ultimate goal of the proposed research is to establish a unified framework customized specifically for the chain-type long range sensor network that is capable of energy efficient operations across multiple layers of network stack and is adaptive to a wide variety of application-driven data delivery models, including schedule (time)-driven, query-driven, and event-driven applications.

To achieve the objectives of the proposed research, we need to meet the key challenges outlined above. This unique class of sensor networks is characterized by the chain-type topology resulting from deliberate deployment of sensor nodes along an elongated physical environment or infrastructures to monitor certain application specific events or phenomena of interest. The elongated area of interest may extend from a few tens to a few hundreds of

miles in length and may include various critical infrastructures and natural resources, such as highways, rivers, coast lines, stretched port areas, and land borders.

The strategy of the proposed research will be to take full consideration of the unique chain-type topology so as to overcome additional constraints such sensor networks may present as well as to utilize potential benefits such sensor networks may be able to offer. We will first explain the need for a new network architecture for chain-type sensor networks because existing architectures and their underlying protocols are not suitable for the unique chain-type long range sensor networks. By considering performance metrics in network lifetime and deployment cost, we propose a novel hierarchical architecture for chain-type sensor networks. to design networking protocols to enable key network components, in this case, sensor nodes, cluster head nodes, and base stations, to accomplish the task of network initialization and then to work smoothly under normal operation phases. The goal in developing networking protocols for chain-type sensor networks is to recognize and make full use of the smart cluster head deployment strategy employed to maximize the network lifetime. We intend to develop a unified framework appropriate for all type of applications: schedule (time)-driven, query-driven, and event-driven.

We will also develop an energy efficient media access control (MAC) protocol for chain-type wireless sensor networks. This MAC protocol is a set of novel TDMA scheduling protocols that takes full advantage of the channel reuse inherent in the chain-type topology to develop energy efficient and high data throughput MAC protocol for sensor data transmission. The synchronized TDMA scheduling allows the nodes to power on only when it is scheduled to send and receive; hence it results in extra energy saving. Within a cluster of nodes, parallel transmission is made possible because of the linear distribution of the nodes within the chain-type topology and yields the desired high throughput.

3. Hierarchical Architecture for Chain-Type Wireless Sensor Networks

The long range of the chain-type network will prohibit each sensor node to communicate directly with the data sink because of the high cost of the long range radio transmission. It therefore requires the implementation of relay in order to efficiently transport sensor data to the data sink. However, the directional transmission along the chain of sensor nodes will create significant latency if the chain is long. Therefore, the number of relays needs to be limited so as to control the overall latency in data gathering. To balance between the number of relays and the overall latency, it is natural that a hierarchical architecture be adopted for the chain-type sensor networks. In this research, we shall develop a novel hierarchical architecture that is suitable to facilitate energy efficient and low delay gathering of sensor data from chain-type sensor networks. To maximize the lifetime of such sensor networks, we also develop a corresponding sensor node deployment strategy so that the sensor nodes in each cluster shall remain alive for approximately the same time duration.

3.1. The Needs for a New Architecture for Chain-Type Sensor Networks

Most recent research activities on the wireless sensor networks have been focusing on the applications in which sensor nodes are randomly deployed in a two-dimensional or three-dimensional concentrated area. The network architecture and protocols developed for these existing applications become ineffective or unnecessarily complicated when applied to the chain-type large scale sensor networks. The mismatch occurs because, in the case of chain-type sensor networks, the nodes are usually deployed at certain strategic sites along a virtually one-dimensional geographical area that may extend to tens to hundreds

of miles. The network topology resulting from such deployment is fundamentally different from the traditional random and usually 2-D planar deployment plan.

Among the key factors that would influence the development of new network architecture, the topological layout of the sensor nodes usually determines the overall architecture of a network. However, network architecture and the corresponding protocols are also dependent on other attributes of the sensor nodes such as energy constraints, communicating and computing capabilities, data aggregation models, and data delivery models [31]. In the case of chain-type sensor networks, the long stretch of the sensor nodes will demand that network architecture be effective to reach out to the edge nodes of the network which usually are far away from the data sink with a restricted route to reach the data sink. Therefore, it is natural that a hierarchical architecture be developed so that the network is scalable in order to suit for a wide variety of applications that may require the chain-type sensor nodes deployment.

Among the existing schemes, a class of cluster-based hierarchical routing protocols has been developed for homogeneous sensor networks that exhibit excellent scalability for large scale sensor networks [8, 11, 13, 32, 33]. In this case, all sensor nodes have equal capabilities. The key advantage in these protocols is their ability to form the optimum number of clusters among sensor nodes randomly deployed in a concentrated area so that the overall network energy consumption can be minimized. When applied to the chain-type large scale sensor networks, two problems will arise. First, these schemes assume that a cluster head node is one single hop away from the base station [8, 13, 33]. Namely, each cluster head node is able to communicate with the base station directly. It is evident that such an assumption is unrealistic for the chain-type sensor networks under consideration because the distance between the base station and most clusters of sensor nodes is simply too great for a single hop radio transmission. Second, the deterministic nature of the sensor node deployment does not allow self-organization of the clustering for optimal transmission. The existing algorithms that can effectively determine the optimal number of clusters within a network are therefore again not applicable to chain-type sensor networks.

Another class of hierarchical architecture and routing protocols has also been developed, and in this case, for heterogeneous sensor networks in which some sensor nodes (e.g., cluster heads) have more enhanced capabilities than the others [12, 13]. The needs for heterogeneous sensor networks usually arise when the deployment of some high capacity sensor nodes can significantly improve the overall performance of a given type of sensor networks. A recent scheme developed for heterogeneous sensor networks has an elegant analysis on clustering-based scenarios with linear (1-D), planar (2-D), and spatial (3-D) clusters. The paper by Ding and et al. [13] was mainly based on a single cluster of nodes and no analysis was provided for inter cluster communication. However, in the case of chain-type sensor networks, it is necessary to develop inter cluster communication between the cluster heads since it is impractical, as we will demonstrate later, to have just one hop communication between the base station and most cluster heads in the chain-type sensor networks. The linear fashion deployment of sensor nodes results in another one dimensional chain type distribution of the cluster heads. It is therefore necessary to develop new architecture and corresponding network protocols for the unique class of chain-type sensor networks.

3.2. The New Hierarchical Chain-Type Architecture

In this research, we propose an innovative multiple tiered hierarchical network architecture for the chain-type long range wireless sensor networks. The first consideration for the

proposed hierarchical architecture is scalability for this unique class of sensor networks. For simplicity of analysis, our descriptions in this proposal are based on a three-tier hierarchical architecture. The lowest tier consists of common sensor nodes which are grouped into clusters at designated strategic sites along an elongated chain-type area. Each cluster has a cluster head node (CHN) with enhanced capabilities. All CHNs form the second tier. The third tier consists of the base stations (BSs). The SNs perform data sensing tasks and report to local CHNs. CHNs aggregate the data streams from the related SNs and then forward the aggregated local-view data stream to a BS.

It is clear that such hierarchical architecture can be easily expanded to include more BSs in the highest tier for a long range chain-type sensor networks. Additional tiers can also be added between CHNs and BSs based on specific application needs. Therefore, the proposed architecture is easily scalable to increase the size of the network. In this case, the size of the network corresponds to the length of an elongated topology.

In general, we assume that both SNs and CHNs are battery-powered and thus have limited energy supply. However, we assume that the BSs have no such constraints. In addition, we also assume that SNs, CHNs, and BSs in this scenario are generally stationary once they have been deployed. A mobile BS scenario can also be deployed [34,35] when the cost and needs of such operation can be justified. However, such scenarios are not considered in this research.

To ensure that the proposed hierarchical architecture is not only scalable, but also energy efficient, we need to solve the following problems:

- 1) What is the optimum communication mode(s) between CHNs and BSs?
- 2) How to balance the uneven energy consumption among CHNs via strategic sensor node deployment?
- 3) How to design a set of network protocols which enable the network to accomplish the initialization and operation stages based on the selected communication modes and sensor deployment strategy?

Figure 1 shows the architecture of a three-tier chain-type wireless sensor network. Without loss of generality, we assume in our analysis that there is only one BS which is without energy constraint, and that both SNs and CHNs are battery-powered. However, we assume that the CHNs are equipped with higher capability in both computation and communication and that the nodes of the same type (CHNs or SNs) are homogeneous (equal capability).

We shall focus our analysis on the second tier and the third tier, namely, the communications between CHNs and BS. This is because of the following reasons:

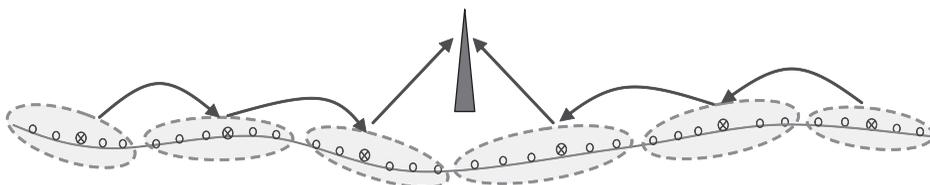


Figure 1. The architecture of chain-type wireless sensor network.

- 1) CHNs have substantial impact upon the service time of the overall network than SNs. Although CHNs are generally equipped with higher capability, they consume energy at a much faster rate because they are responsible for data collection and aggregation within the cluster. Furthermore, they perform the task of energy-extensive long-haul transmission to BS. When a SN runs out of energy, its CHN can still collect information from other SNs and provide local-view data to BS. However, if a CHN runs out of its energy, the entire coverage of the cluster is lost and the integrity of the network service is compromised.
- 2) The elongated chain-type network topology imposes more stringent requirements on the choice of the communication modes between CHNs and BS, rather than that between SNs and CHNs. In the unique scenario under consideration by this proposal, clusters are more sparsely distributed along an elongated chain-type area which may extend a few tens of miles or even longer.

3.3. Communication Mode Selection and Smart Cluster Head Deployment

We illustrated in the previous section that the proposed hierarchical architecture is scalable for chain-type wireless sensor networks. We also showed that we should focus on research related to the communication and networking between CHNs and BS in order to develop energy efficient operations that would maximize the life time of the sensor networks. In this section, we will address several key technical issues and propose corresponding research strategies to resolve these. The technical issues associated with the hierarchical architecture include the following:

- 1) The selection of communication modes between CHNs and BS for energy-performance tradeoff.
- 2) The deployment policy for the CHNs to address the problem of uneven energy expenditure among CHNs.
- 3) Performance evaluation of the hierarchical architecture under the proposed communication mode and deployment strategy.

3.3.1. An Energy Model for Sensor Node Communication. We adopt the same model as the one by Lindsey [8] for the transceiver of a node. With this model, at the transmitter, the energy is dissipated when running the radio electronics and the power amplifier; at the receiver, the energy is dissipated only when running the radio electronics. Thus, to transmit a q -bit packet over a distance d , a node consumes:

$$e_{tx}(q, d) = \begin{cases} q\alpha + q\beta_1 d^2, & d < d_0 \\ q\alpha + q\beta_2 d^4, & d \geq d_0 \end{cases} \quad (1)$$

And to receive this packet, a node consumes:

$$e_{rx}(q, d) = q\alpha \quad (2)$$

In (1) and (2), α is the energy consumed by the radio electronics to process 1 -bit information. β_1 and β_2 are two constants depending mainly on the propagation environment, antenna parameters of transmitter and receiver. The parameter d_0 is the crossover distance. When the distance between the transmitter and receiver is less than d_0 , the free space channel model $\beta_1 d^2$ is used. Otherwise, the multipath fading channel $\beta_2 d^4$ is used. The parameter d_0 is calculated as 86.2 meters according to the current available radio technology [8]. Therefore,

in our scenario, for communications within a cluster of small to medium size, both the free space model and the multipath model can be used; for communications between CHNs and BS, the multipath model is adopted to account for the long range transmissions.

3.3.2. Definition of Network Lifetime. In a three tier chain-type long range sensor network, in order to effectively cover a long distance of elongated area, the CHNs and BSs are assumed fixed in location. Therefore, when a SN runs out of energy, its CHN may still continue to collect data from other SNs and feed the BS with local-view data. However, if a CHN runs out of energy, the entire coverage of the cluster is lost, even though some SNs may still be alive and functioning. Therefore, the network lifetime of the hierarchical networks is fully determined by the operation lifetime of the CHNs.

Assume there are Q CHNs $\{h_i, i = 1, \dots, Q\}$ distributed uniformly in Q clusters within a chain-type wireless sensor network and the initial energy allocated to each CHN is $E(0)$. The energy consumption per unit service time can be denoted as $\{e_i, i = 1, \dots, Q\}$. The lifetime of each CHN is therefore $\{l_i = E(0)/e_i, i = 1, \dots, Q\}$ units of service time. Note that $\{e_i, i = 1, \dots, Q\}$ varies under different communication modes, and will affect the lifetime of CHNs.

In this research, we define the overall network lifetime as:

$$L_m = \min\{l_i = E(0)/e_i, i = 1, \dots, Q\}_m \quad (3)$$

Hence, the network lifetime L_m is the service time of the entire network until any one of the CHNs runs out of its energy. Note that L_m is a function of the underlying communication mode m since different communication modes will yield different L_m . The impact of communication modes on network lifetime will be presented next.

3.3.3. Selection of Communication Modes based on Energy Performance Tradeoff. The abstract network topology of CHNs and BS is shown in Fig. 2 with ideally deployed locations of CHNs that are R meters apart. It is obvious that the elongated chain-type wireless sensor network can be represented well by a linear array network. The theoretical derivations are based on following assumptions:

- 1) The total number of relaying hops from the farthest CHN to BS is N . $N \approx D/R$ can be realized by properly placing the BS in the center of the array. D is the distance from the farthest CHN to BS. R is the ideal radio range of each CHN.
- 2) Each Cluster has only one CHN, thus $Q = 2N$ because of the symmetric architecture of the ideal network.
- 3) One service cycle is the time interval that each CHN sends one q -bit packet to BS and Q packets in total are received by the BS.

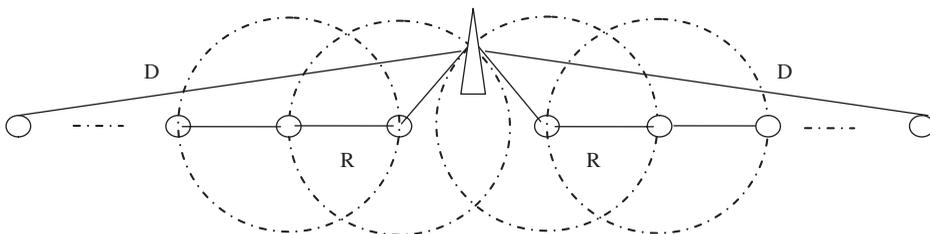


Figure 2. Topology of chain-type wireless sensor network.

In the case of the single hop communication mode, all CHNs communicate with the BS directly. The critical CHN that determines the network lifetime is the remotest one from the BS. During a service cycle, the critical CHN only sends one q -bit packet to BS and spends energy:

$$e_s = q\alpha + q\beta_2 N^4 R^4 \quad (4)$$

Equation (4) shows that the energy expenditure in single hop mode increases with the 4th power of the number of hops N at the given radio range R .

When the multi-hop mode is adopted, the farther CHNs relay their packets to BS via the closer CHNs. The critical CHN which decides the network lifetime is the closest one to the BS. During a service cycle, the critical CHN needs to relay $N - 1$ packets from its downstream CHNs plus one packet from itself to BS. It spends energy

$$e_m = (2q\alpha + q\beta_2 R^4)(N - 1) + (q\alpha + q\beta_2 R^4) = q\alpha(2N - 1) + q\beta_2 NR^4 \quad (5)$$

Equation (5) shows that the energy expenditure in multi-hop mode increases linearly with the number of hops N at the given radio range R .

When the hybrid mode is used, all CHNs switch between the single hop mode and the multi-hop mode based on some rule of operation. When single hop is used the CHNs near the BS are relieved of their relaying burden, and when the multi-hop mode is used the CHNs farther from the BS are relieved of their burden of long range transmissions to the BS. Hence by alternating between these two modes it is possible to obtain a more uniform load distribution and compensate the uneven energy consumptions among CHNs.

Assume CHNs use the single hop mode in μT service cycles and the multi-hop mode in $(1 - \mu)T$ cycles, where $0 \leq \mu \leq 1$. For a CHN located at a distance of nR from the BS, where $1 \leq n \leq N$, the energy it spends during μT cycles of the single hop mode is

$$e_{h,s}(T, nR) = \mu T (q\alpha + q\beta_2 n^4 R^4) \quad (6)$$

And the energy it spends during $(1 - \mu)T$ cycles of the multi-hop mode is

$$e_{h,m}(T, nR) = (1 - \mu)T ((2q\alpha + q\beta_2 R^4)(N - n) + (q\alpha + q\beta_2 R^4)) \quad (7)$$

Thus the total energy this CHN spends in T cycles is

$$e_h(T, nR) = e_{h,s}(T, nR) + e_{h,m}(T, nR) \quad (8)$$

Both $e_{h,s}(T, nR)$ and $e_{h,m}(T, nR)$ are convex functions of n . Therefore, the energy spent by the critical node is function of μ and can be obtained by minimization as follows:

$$\bar{e}_h = q(e_{m,\max} e_{s,\max} - e_{\min}^2) / (e_{m,\max} + e_{s,\max} - 2e_{\min}) \quad (9)$$

where $e_{\min} = (\alpha + \beta_2 R^4)$ is the minimum energy required by a CHN to send 1 bit over the distance of R , $e_{s,\max} = \mu T (\alpha + \beta_2 N^4 R^4)$ is the maximum energy required by the critical CHN to send 1 bit to the BS in the case of single hop mode, and $e_{m,\max} = \alpha(2N - 1) + \beta_2 NR^4$ is the maximum energy required by the critical CHN to send 1 bit to the BS in the multi-hop mode.

It is easy to show that $e_{\min} < e_{m,\max} < e_{s,\max}$. It has been shown that the hybrid communication mode is useful for various sensor network applications when the distance between the hops is relatively short [12]. However, in a typical application scenario for the proposed chain-type sensor networks, the distance between the CHNs R will be in the range of 100 to 1000 meters. In this case, we shall have $e_{\min} \ll e_{m,\max} \ll e_{s,\max}$ and thus we can conclude that $\bar{e}_h \approx e_{m,\max}$. Therefore, considering the manufacturing cost of radio electronics capable of switching between single hop and multi-hop for hybrid communication, we shall adopt the multi-hop communication modes for the chain-type sensor networks in order to achieve the best energy performance tradeoff.

3.3.4. Smart Cluster Head Deployment with Multi-hop Communication Mode. Once we decide to adopt the multi-hop communication mode for CHNs, we will need to resolve the serious problem that the CHN closest to the BS will die first because of its heaviest burden in relaying data transmission from other CHNs to BS. The lifetime of this CHN shall determine the lifetime of the entire group of the CHNs served by the BS. Likewise, the CHN next to this CHN will endure the second heaviest burden in relaying data transmission and shall die next. In theory, when each CHN has the same amount of data to transmit to the BS, the lifetime of the CHNs will decrease in a linear fashion from the CHN closest to the BS to the CHN farthest from the BS.

In this research, we propose a new strategy of deploying CHNs in a smart way with each cluster in order to share the extra burden of relaying load. This new strategy is to make use of redundant CHNs to balance the energy consumption in the multi-hop communication mode. In principle, we can deploy more redundant CHNs in clusters closer to BS and less redundant CHNs in clusters farther from BS. With an unequal number of redundant CHNs, those clusters that support more relay tasks shall have increased network lifetime.

Based on this principle, if we assume there are N clusters uniformly located along the chain-type area, the local-view data load generated at each cluster is nearly uniformly distributed, and the farthest cluster has one CHN, then, we can deploy linearly $\{N, N-1, \dots, 1\}$ CHNs at clusters from the closest to the farthest, so that each CHN shares approximately the same load and all clusters run out of energy at about the same time. We shall call such strategy smart cluster head deployment since it takes into account the distance of each cluster to the BS. Figure 3 shows the illustration of this smart sensor node deployment strategy with redundant CHNs at locations closer to BS to balance the uneven transmission load. The total number of CHNs deployed is $Q_{m,r} = 2 \sum_i^N N_i = N^2 - N$ in this case, instead of $2N$ in the original deployment. Hence, to send a q -bit packet to BS, the energy spent by a CHN is:

$$e_{m,r} = 2q\alpha + q\beta_2 R^4 \quad (10)$$

In this case, the energy spent by a CHN is independent of the number of hops N because extra redundant CHNs are added to share the relaying load. Therefore, the network lifetime will be:

$$L_{m,r} = E(0)/2q\alpha + q\beta_2 R^4 \quad (11)$$

We will demonstrate later that, even with increased network deployment cost, such smart sensor node deployment is still an efficient approach to balance the energy consumption among clusters and thus improves network performances.

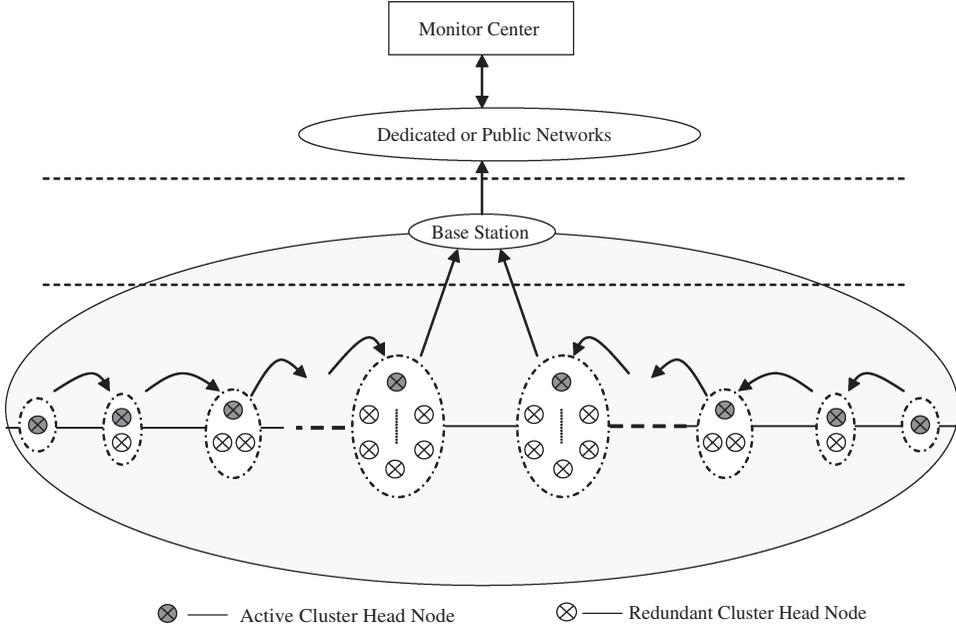


Figure 3. Illustration of Smart Sensor Node (CHNs) deployment.

3.4. Performance Evaluation of Proposed Architecture, Communication, and Deployment

The performance evaluation of the proposed hierarchical architecture under multi-hop communications between CHNs and BS as well as the smart node deployment shall be carried out to validate the proposed architecture, communication mode selection, and smart sensor node deployment.

We will begin with some theoretical derivations. We normalize both network lifetime and deployment cost with the same initial energy per unit data transmission. The normalized network lifetimes for the four communication modes are:

$$\bar{L}_s = 1/e_{s,max} \tag{12}$$

$$\bar{L}_m = 1/e_{m,max} \tag{13}$$

$$\bar{L}_h = (e_{m,max} + e_{s,max} - 2e_{min}) / (e_{m,max}e_{s,max} - e_{min}^2) \tag{14}$$

$$\bar{L}_{m,r} = 1 / (e_{min} + \alpha) \tag{15}$$

Figures 4 and 5 show the results of normalized network lifetime when the hop ranges are 1000 meters and 100 meters respectively. Based on these, it is clear that $\bar{L}_{m,r} > \bar{L}_h \approx \bar{L}_m > \bar{L}_s$ for both cases. By deploying redundant nodes non-uniformly at clusters, each cluster runs out of energy at about the same time. Therefore, the network achieves a near constant lifetime; however, with the increase of network deployment cost. The single hop mode achieves the shortest network lifetime, because the critical CHN expends more energy for long haul transmission to BS. The multi-hop mode achieves

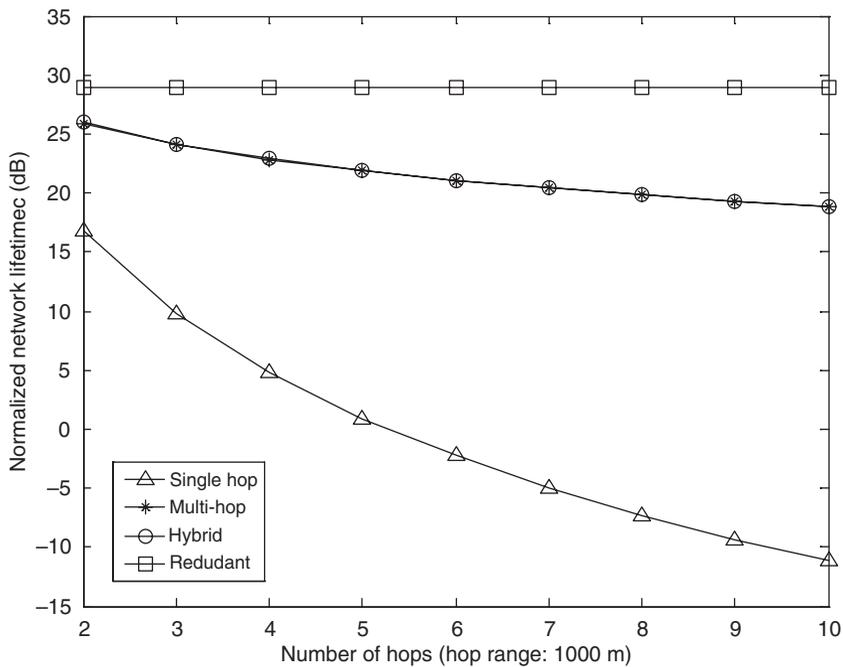


Figure 4. Normalized network lifetime versus number of hops at radio range 1000m.

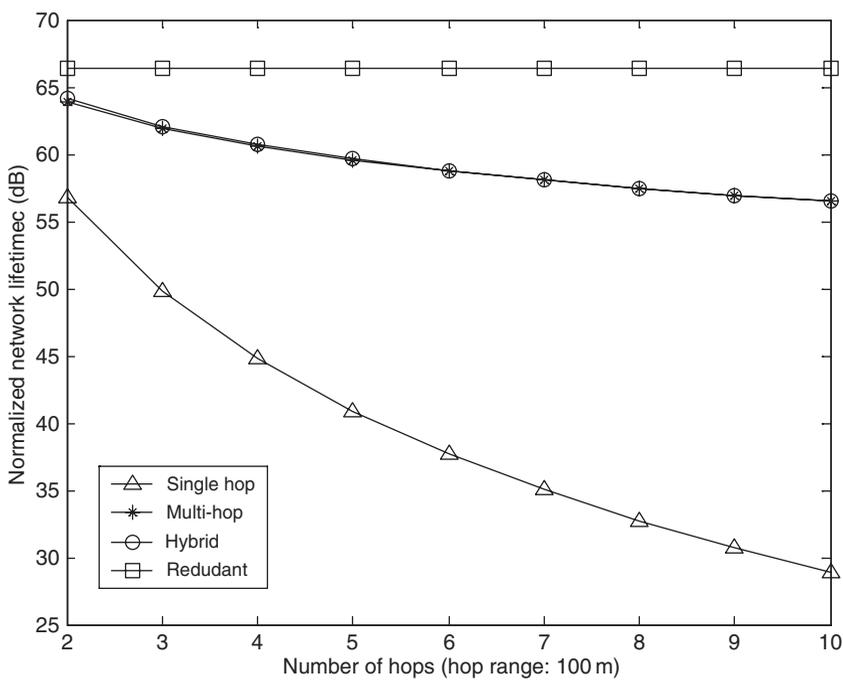


Figure 5. Normalized network lifetime versus number of hops at radio range 100m.

better lifetime performance than the single hop because the extra energy expenditure in relaying other packets of CHNs over distance R to BS is less than transmitting the same data from the farthest location.

Similar to the normalized network lifetime, we can normalize the cost function with $QCq E(0)$ for a fair comparison. The normalized cost functions for four communication modes are:

$$\bar{f}_s(Q, L_s, C) = e_{s,\max} \tag{16}$$

$$\bar{f}_m(Q, L_m, C) = e_{m,\max} \tag{17}$$

$$\bar{f}_h(Q, L_h, C) = (e_{m,\max}e_{s,\max} - e_{\min}^2)/(e_{m,\max} + e_{s,\max} - 2e_{\min}) \tag{18}$$

$$\bar{f}_{m,r}(Q_{m,r}, L_{m,r}, C) = (e_{\min} + \alpha)Q_{m,r}/Q = (N/2 - 1)(e_{\min} + \alpha) \tag{19}$$

Figure 6 shows the results of normalized network lifetime when the hop range is 1000 meters. It is clear that $\bar{f}_{m,r} < \bar{f}_h \approx \bar{f}_m < \bar{f}_s$. Notice that although the smart deployment of redundant nodes at all clusters increases the network cost, the gain from its prolonged network lifetime overwhelms this cost. This still yields the minimum cost function compared to the other three communication modes with the uniform deployment of CHNs. Due to restrictive assumptions, these conclusions from theoretical derivation will serve only as the guideline for the design of network protocols.

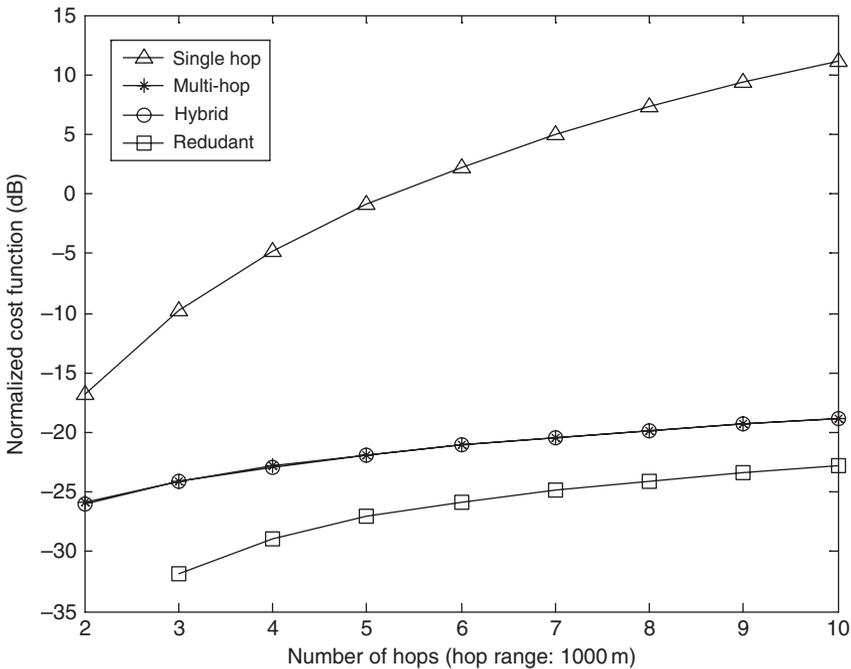


Figure 6. Normalized cost function versus number of hops at radio range 1000m.

4. Networking Protocols

In this section, we first propose a set of network protocols serving as a unified framework for the time-driven chain-type large scale sensor networks. In the time-driven multi-hop sensor networks, each SN sends data periodically to its CHN, and then, CHN aggregates multiple data streams and forwards the aggregated data stream to BS in a multi-hop fashion. We will extend the protocols to query-driven and event-driven applications. In these cases, sensor data is sent to BS only when a query is received or an event is triggered.

Figure 7 shows the operations of the network in time sequence. It first runs an initialization phase when the network is self-organized. Then it runs periodically the normal operation phase when sensor data collection occurs.

4.1. Initialization Stage

In the initialization phase, the network accomplishes the network synchronization, self-organization of CHNs, self-organization of SNs, and routing table establishment. The protocols in this phase consist of following steps:

- Step 1: *Synchronization* – Each BS broadcasts beacons including synchronization and other network information. All SNs and CHNs within a BS's coverage area synchronize with it. All BSs may be synchronized through GPS;
- Step 2: *Self-organization of CHNs* – Each CHN broadcasts its own ID and other capability information. From the receiving signal's level, a CHN is able to identify all intra-cluster CHNs (redundant CHNs). Then they shall elect one as the active CHN. In this research, we propose a simple scheme based on the value of the CHNs' ID. A CHN sets up a table which contains the ordered IDs of all the intra-cluster CHNs. The active CHN is elected from this ordered table according to a specific rule. For example, we can set a top-down rule which chooses a CHN as the active one in the order from the highest ID value to the lowest. In addition, each active CHN knows its unique cluster ID and uses that for route discovering later. It can either be assigned by the BS, or just be set as the highest ID value of CHN according to that ordered table. Contention-based MAC protocols are used in this phase.
- Step 3: *Self-organization of SNs* – Each active CHN broadcasts beacons within its coverage. A SN associates itself to a CHN from which it receives the highest signal power. After a short period, the active CHN collects all the information of its associated SNs. Contention-based MAC protocols are used in this phase.

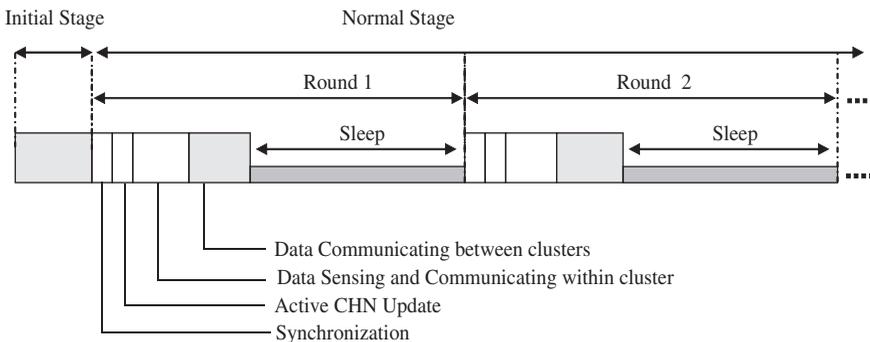


Figure 7. Time sequence of operations of network protocols for chain-type sensor network.

Step 4: *Routing Table Establishment* – Each active CHN initiates a routing discovering procedure. For a chain type network, as it can be represented well by a linear array network, it is easy for each CHN to obtain a routing table, from which it knows all of its upstream and downstream CHNs. It is important to note that the source and destination addresses include cluster IDs. This routing table will be updated during a normal operation stage according to the specific routing algorithms employed. Each active CHN broadcasts the routing information so that non-active CHNs store this information in their own memory. After this, all non-active CHNs switch to the sleep mode. Contention-based MAC protocols are used in this phase.

4.2. Normal Stage

In a normal stage, the network runs in periodic rounds of data collection. Each round of the network protocol includes the following steps:

- Step 1: *Synchronization* – All CHNs wake up from the sleep mode and synchronize with the base station, which periodically sends out the beacons at the beginning of each round. Then each CHN updates its round counter;
- Step 2: *Active CHN update* – The active CHN broadcasts “active CHN update” information when its residual energy drops below a preset threshold, i.e., 5% of its initial energy. Then the CHN having the closest ID value to that of the active CHN becomes a new active CHN from this round on. All other CHNs switch into sleep mode until the next round;
- Step 3: *Data sensing and communicating within cluster*– Each active CHN manages data sensing and communication tasks of the SNs and performs data aggregation tasks within the cluster. Either scheduled MAC protocols or contention-based MAC protocols can be used in this stage.
- Step 4: *Data communicating between clusters*– Each active CHN transmits the aggregated data multi-hop to BS. During this phase scheduled MAC protocols or contention-based MAC protocols can be used. For scheduled MAC protocols, it is BS that assigns the sequence of transmissions. For contention-based MAC protocols, they are expected to combat the problems of hidden terminal and exposed terminal and incorporate the sleep mode operation to achieve better energy efficiency. An active CHN will not switch to the sleep mode until it has transmitted its own packet and relayed all loads of its downstream nodes. Therefore, different CHNs have different lengths of sleep time according to the total data load and the adopted MAC protocol.

4.3. Extension to Query-Driven and Event-Driven Applications

For query-driven and event-driven applications, intra-cluster and inter-cluster communications may occur simultaneously due to the lack of coherent time scheduling. This may cause collision between intra- and inter-cluster communications. Figure 8 shows an example of the interactions between the intra-cluster and inter-cluster communications. On one hand, if multiple short range intra-cluster communications start first, say, B and D are sending data to A and E respectively, C can not hear their transmission and may start sending data to E. Then, all on-going intra-cluster communications within the shadow area will collide and retransmissions are required. This leads to more energy waste. On the other hand, if long range inter-cluster communication C to F starts first, then all intra-cluster communications within the shadow area will be restricted, which leads to longer latency.

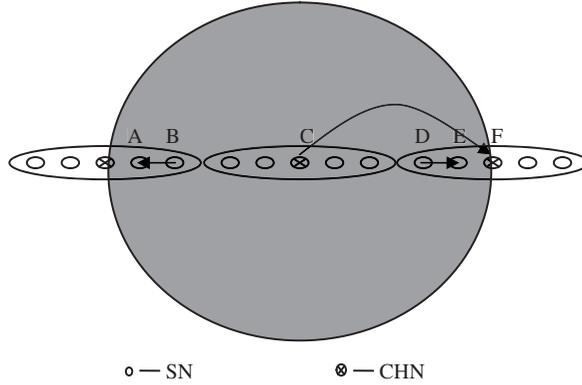


Figure 8. Interactions between intra- and inter-cluster communications.

To achieve better energy efficiency and latency, we need to decouple the interactions between intra and inter communications. We propose to separate the intra- and inter-cluster communications into two distinct frequency channels 1 and 2 as shown in Fig. 9, so that they do not interact with each other. The reason code division channels are not suitable is because the significant “Near-Far” effect [36] for the chain-type topology. This will lead to worse bit error rate and waste of retransmission energy. Figure 9 shows the time sequence of network protocols suitable for all three types of applications in the normal operation stage. One disadvantage of this protocol is that each CHN must be equipped with two radios. In the case of time-driven (scheduled) applications, there is no need for CHNs to have two radios. However, for all three types of applications, SNs require only one radio.

4.4. Performance Evaluation of Networking Protocols

To effectively evaluate the performance of the networking protocols, we need to select an appropriate application scenario and corresponding MAC protocols for network simulation. In a separate paper, we will present a novel TDMA scheduling protocol for the

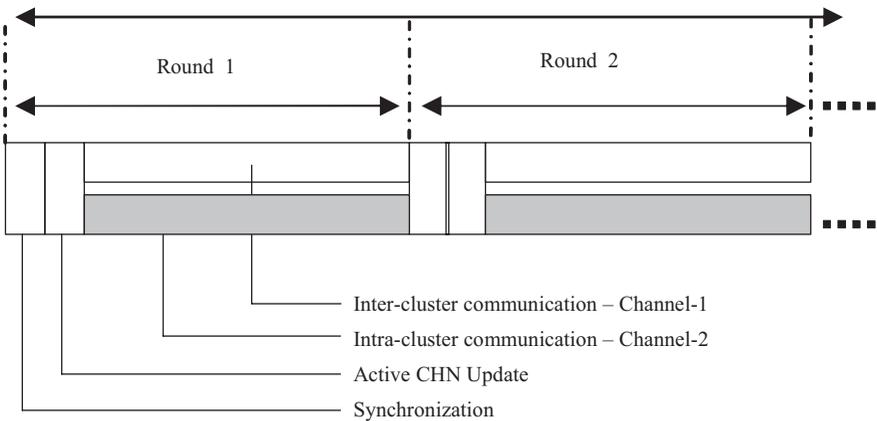


Figure 9. Time sequence of network protocols for all applications.

unique chain-type sensor networks. This TDMA scheduling protocol is able to achieve energy efficient and high throughput sensor data transmission. The synchronized TDMA scheduling allows the nodes to power on only when it is scheduled to send and receive and therefore results in additional energy savings. Within a cluster, parallel transmission is made possible because of the linear distribution of nodes within the chain-type topology and this yields the desired high throughput. Notice that only chain-type hierarchical architecture is able to facilitate such an energy efficient and high throughput TDMA scheduling.

As the networking and scheduling protocols interact with each other intimately, it is not appropriate to perform separate simulations for the networking protocols only. Instead, we shall carry out one integrated simulation employing both networking and scheduling protocol sets. Two major indicators are important performance measures for the protocol evaluation: normalized energy consumption per bit of data transmission and aggregated throughput per node within the sensor network. In the following, we shall compare the proposed protocols with SMAC, a well-known MAC protocol developed specifically for sensor networks [2]. We will show that the proposed protocols are able to significantly outperform SMAC protocol under different duty cycles. The details of the evaluation are described in the next section.

5. The Proposed TDMA-Based MAC Protocols

5.1. The Existing Schemes of MAC Protocols

Energy efficiency is the core of the MAC protocol design for wireless sensor networks. An excellent analysis of how the energy is wasted during the execution of the MAC protocols has been presented in a recent paper by Ye, Heidemann, and Estrin [2]. In this paper, it is claimed that the energy is wasted mainly in four aspects: idle listening, collision, overhearing, and protocol overhead. Idle listening is due to a typical working cycle of a sensor network in which the nodes will be in idle state for a long time if nothing is sensed. Measurements have shown that idle listening consumes about 50%–100% of that by receiving. Collisions occur when two nodes transmit simultaneously and interfere with each other's transmission. The data packets are corrupted and discarded, and the subsequent re-transmission is required which increases energy consumption. Overhearing refers to the case when a node receives data packets that are destined to other nodes. This can be simply avoided by turning off its radio on such occasions. Protocol overhead is necessary to establish the radio communication through control packets (RTS/CTS/ACK). The protocol overhead does not contain sensor data but consumes additional energy.

Current MAC protocols developed for sensor networks seek different approaches to solve these four problems in energy wasting. They can be broadly divided into contention-based [2, 37] and TDMA [7, 38] MAC protocols.

IEEE 802.11 distributed coordination function (DCF) [39] is a standardized contention-based protocol which is based on carrier sensing multiple access (CSMA) and collision avoidance (CA). CSMA is implemented by both virtual and physical carrier sensing, and CA is achieved through RTS/CTS handshake of the MACAW protocol [18]. CSMA/CA in 802.11 effectively reduces collisions in multi-hop ad hoc networks. In addition, the DCF supports the power saving mechanism (PSM), which further reduces the energy wasted in continued idle listening by adopting periodical listening. However, PSM in the DCF is only supported in single-hop ad hoc networks. Tseng [40] improved

the PSM in multi-hop networks. Singh proposed the PAMAS [41] which reduces the energy wasted in overhearing by shutting off the radio for a duration indicated by the RTS/CTS packets of neighboring nodes. Ye et al. and van Dam et al. proposed the S-MAC [2] and T-MAC [37], respectively, which integrate the coordinated periodical listen, overhearing avoidance [41], and CSMA/CA [39] to reduce the energy wasted in idle listening, overhearing, and collisions. In contrast, the TDMA scheme proposed in this paper will completely eliminate the overhearing and collisions, and reduce the idle listening to a minimum level.

TDMA MAC protocols are inherently collision free. LEACH [7] and Bluetooth [42] are TDMA protocols which use a cluster head to schedule the single hop communications within a cluster. In comparison, our scheme is to schedule the multi-hop communication that has been selected as the mode of communication for cluster heads in the chain-type sensor networks. LEACH allows the frame size to change with the number of sensor nodes in a cluster, while Bluetooth fixes the frame size to accommodate at most 8 nodes, which however limit their scalability. Arisha [38] partitions the network into large clusters. In each cluster, a gateway node schedules the multi-hop communications between sensor nodes and the gateway node. The TDMA schedule is based on the information of the sensor nodes' energy level, traffic load and so on, which are reported periodically from each node to the gateway nodes through single hop communications. This scheme is not applicable to chain-type sensor networks since this will result in significant energy consumption and the requirement of high radio capability of each node distributed along an elongated chain-type network as will be discussed in Section 3.2. Furthermore, the fixed length frame must be designed to accommodate the largest number of nodes within a cluster. Clearly, both strategies limit the scalability for chain-type sensor networks and therefore are not applicable.

5.2. The Proposed TDMA-Based MAC Protocols

The proposed TDMA scheduling protocols are explicitly developed for the chain-type sensor networks to take full use of the available channel reuse inherent in the chain-type sensor networks. We aim at developing an energy efficient and high throughput scheme for data transmission within the chain-type sensor networks. The synchronized TDMA scheduling allows the nodes to power on only when it is scheduled to send and receive and therefore results in additional energy savings. Within a cluster, parallel transmission is made possible because of the linear distribution of nodes within the chain-type topology and this yields the desired high throughput. Notice that only the chain-type hierarchical architecture is able to facilitate such an energy efficient and high throughput TDMA scheduling.

To be consistent with the hierarchical architecture, sensor node deployment, and network initialization of the chain-type sensor networks as we described in Section 3, we make the following assumptions on the network model in order to introduce the proposed TDMA scheduling schemes:

- 1) An N-1 hop chain topology of a wireless sensor network shall consist of N nodes. The Nth node is the scheduling node like CHN as shown in Fig. 1. Each node is equipped with a single half-duplex transceiver. The scheduling node has a large radio range to reach all of its associated nodes, whereas, non-scheduling nodes are only capable of covering a one hop distance. Namely, both the communication range and interference range are equal to one hop of distance.

- 2) Each node has a unique sequential index number $\{1, 2, 3, \dots, N\}$, which can be obtained during the network initialization stage or during the network operation stage. Each node also has the knowledge of the number of data transmission slots a frame contains, which is either preset or obtained in the network initialization stage.

Figure 10 shows the frame structure of the proposed TDMA scheduling protocol. Each frame consists of four sub-fields: Synchronization, Query, Data Transmission, and Join. During the Synchronization period, the scheduling node broadcasts the beacon signal to synchronize all associated nodes. During the Query period, the sink node may send out query or other control information to all nodes. The Data Transmission period consists of several slots, during each slot there may be multiple *autonomously* scheduled transmissions. The scheduling of simultaneous transmissions makes full use of the chain-type topology and will be explained in detail next. The Join period is for new members that may be added to the group.

Note that the proposed TDMA scheduling protocol does not require the scheduling node to obtain information on the energy level, the traffic load, or transmission requests, nor does it arrange any scheduling tasks during operation time as in some of the existing schemes [7, 38]. The scheduling node is only used to assign each node a unique sequential index number during the network initialization stage and broadcast query or other information during the operation stage. Once a node has this unique index number, it will *autonomously* schedule its own transmission and reception without affecting the operation of other nodes.

We consider TDMA scheduling for both unidirectional and bidirectional transmission cases. The unidirectional case is for node-to-sink communications such as data gathering while the bidirectional case is for local broadcast communications such as collaborative signal and information processing. To accommodate the flexibility in employing either the frequency channel or the code channel, we will develop the corresponding scheduling schemes for both cases.

5.2.1. Unidirectional TDMA scheduling. In a unidirectional communication pattern, all nodes report their data multi-hop to the scheduler node or sink node (CHN). We first describe the scheduling scheme for the frequency channel and then proceed to the code channel.

The Scheduling Rule for Frequency Channel. The scheduling rule for the frequency channel consists of the following three steps in each frame:

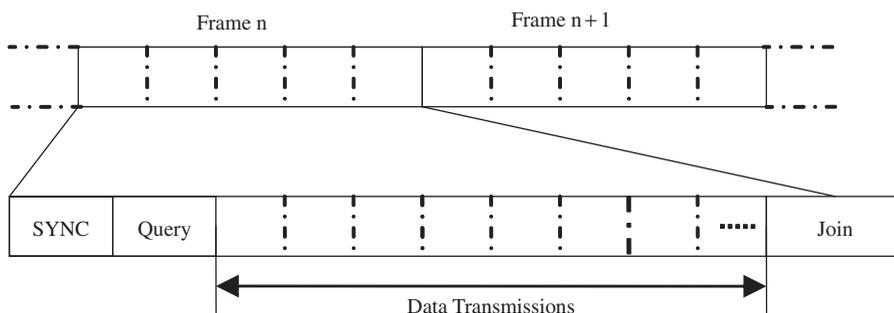


Figure 10. TDMA frame structure.

- Step 1: Initialize the slot index number $slot_id = 0$ and node index number $node_id = 0$;
- Step 2: Choose nodes whose index number match $\{(node_id + freq_reuse_factor \times m) < N, m = 0, 1, 2, \dots\}$ as the senders, where in this case the parameter $freq_reuse_factor = 3$ and nodes whose index number match $\{(node_id + freq_reuse_factor \times m + 1) \leq N, m = 0, 1, 2, \dots\}$ as the corresponding receivers in the current slot of operation;
- Step 3: Increase the count $slot_id + 1$. Check the value of the $slot_id$. If ($slot_id = slot_id_max$), then, stop. The parameter $slot_id_max$ is the maximum number of data transmission slots a frame contains. If ($slot_id \bmod freq_reuse_factor = 0$), then, set $node_id = 0$, and go to Step 2. Otherwise, update $node_id + 1$, then, go to Step 2.

We use a 10-node local cluster of a chain-type sensor network to explain this scheduling rule. Node 9 is assumed as the sink node or CHN. For the frequency channel, the chain-type topology results in a reuse factor of 3. Therefore, nodes that are $3R$ away can simultaneously transmit without interference. Table 1 shows the scheduling rules of the first four slots. In slot 0, nodes 0, 3, 6 transmit data to nodes 1, 4, 7 respectively. In this case, each node is able to send out data again after 3 slots. From the fourth slot, it repeats the transmission pattern of the first slot. In fact, for the i th slot, $i = 0, 1, 2, \dots$, it always repeats the transmission pattern of slot $(i \bmod 3)$. Therefore, a chain-type network with N ($N \in [4, \infty)$) nodes, has just three transmission patterns. In each slot there are always $\lfloor N/3 \rfloor$ pairs of parallel transmissions. This fully exploits the frequency channel reuse and results in a significantly enhanced data throughput.

Notice that the proposed TDMA scheduling scheme is independent of the number N . It is therefore scalable to large size chain-type sensor networks. The above scheduling scheme is also an *autonomous* scheduling scheme. It has the following property that it does not require the scheduling node nor the CHN to schedule other nodes time wise when and how long to transmit or to receive. Instead, each node schedules itself with the only knowledge of its index number $node_id$ and the number of data transmission slots a frame contains: $slot_id_max$. On one hand, this property will simplify the TDMA scheduling protocol and thus save energy, because a lot of signaling overhead such as energy level, traffic load, etc. is no longer necessary. On the other hand, this may lead to energy waste when the duty cycle is low, because a node will always keep active in its scheduled slot even it has completed the data transmission or reception during the given time slot.

To remedy this drawback, we developed an energy conserving method which can be easily integrated into the proposed scheduling scheme. In each slot, the scheduled active nodes shall shut off their radios if they have no data to send. The scheduled receiving nodes shall measure their carrier signals for a very short interval (in microsecond scale), like DIFS_Time of 802.11 DCF mode [39]. If there is no incoming signal detected, they shut off their radios immediately. As a result, under low traffic load, it achieves high energy-efficiency by reducing the idle listening to a very low level. Under high traffic load, it achieves higher throughput by pipelining the maximum number of parallel

Table 1
Frequency Channel (Uni-Direction)

Slot	Sender
0	0, 3, 6
1	1, 4, 7
2	2, 5, 8
3	3, 6, 0

transmissions that do not interfere with each other, while maintaining high energy-efficiency because it completely eliminates the collisions and overhearing.

The scheduling rule for code channel. The proposed TDMA scheduling can also be applied to cases when the radio channel is a code channel. In a multi-hop chain-type sensor network, it is not necessary to assign each node a unique code channel. Instead, the same code channel can be reused for sensor nodes that are two hops away. Hence, we can use just three codes for a chain-type network since such a code assignment can be scalable to networks with any number of nodes.

The scheduling rule for a code channel also consists of the three steps as described in the frequency channel case. The only difference lies in step 2 and step 3, where we need to replace the parameter $freq_reuse_factor = 3$ with $code_reuse_factor = 2$. For simplicity of presentation, the details of these procedures shall not be described.

Table 2 shows the scheduling information of the first four slots for a 10 node chain-type network. After two slots, each node is able to send out data once. Note that a chain-type network using code channels has just two transmission patterns which fully exploit the channel reuse. Within each slot, there are always $\lfloor N/2 \rfloor$ pairs of parallel transmissions.

5.2.2. Bi-directional TDMA Scheduling. In bidirectional communication pattern, nodes exchange data with their neighbors to accomplish some specific tasks such as collaborative information and signal processing. A simple solution will be to adopt the unidirectional scheduling schemes and change the flow direction alternatively. The scheduling node will control the flow direction in Query broadcast. However, a more efficient scheme of true bidirectional transmission will be developed, again by making full use of chain-type topology, in order to achieve an even higher throughput performance.

The principle of such true bidirectional scheduling is to set up one-way parallel transmissions that take place every four hops away. The bidirection scheduling rule for the frequency channel will consist of the following four steps in each frame:

- Step 1: Initialize the slot index number $slot_id = 0$ and node index number $node_id = 0$;
 Step 2: For direction-1, choose nodes whose index number match $\{(node_id + 4m) < N, m = 0, 1, 2, \dots\}$ as senders and nodes $\{(node_id + 4m + 2) < N, m = 0, 1, 2, \dots\}$ as the corresponding receivers in the current slot.
 Step 3: For direction-2, choose nodes whose index number match $\{(node_id + 4m + 3) \leq N, m = 0, 1, 2, \dots\}$ as senders and nodes $\{(node_id + 4m + 2) < N, m = 0, 1, 2, \dots\}$ as the corresponding receivers in the current slot;
 Step 4: Increase the count $slot_id + 1$. Check the value of the $slot_id$. If $(slot_id = slot_id_max)$, then, stop. The parameter $slot_id_max$ is the maximum number of data transmission slots a frame contains. If $(slot_id \bmod 4) = 0$, then, set $node_id = 0$, go to Step 2. Otherwise, update $node_id + 1$, go to Step 2.

Table 2
Code Channel (Uni-Direction)

Slot	Sender
0	0, 2, 4, 6, 8
1	1, 3, 5, 7
2	2, 4, 6, 8, 0
3	3, 5, 7, 1

Table 3
Freq./Code Channel (Bi-Direction)

Slot	Sender	
	Dir-1	Dir-2
0	0, 4, 8	3, 7
1	1, 5	4, 8
2	2, 6	5, 9, 1
3	3, 7	6, 2
4	4, 8, 0	7, 3

Table 3 shows such scheduling rules for the first five slots for a 10 node cluster within a chain-type network. Here, node 9 and node 0 are assumed to be the sink nodes of direction 1 and direction 2, respectively. After four slots, each node is able to send one data in both directions. From the fifth slot on, it shall repeat the transmission pattern of the first slot. Hence, for the i th slot, the transmission repeats the pattern of slot $(i \bmod 4)$. Note that there will always be $N/2$ or $N/2-1$ pairs of parallel transmissions in a slot. If we adopt the unidirectional scheme directly, there will be only $\lfloor N/3 \rfloor$ pairs for each slot of transmission.

When the code channel is adopted by the sensor networks, the scheduling rule for the code channel can be the same as that for the frequency channel. A simple alternative can also be developed. Table 4 shows one of those examples.

5.3. Analysis of the Proposed TDMA Scheduling Protocols

From the scheduling examples shown in Sections 4.2.1 and 4.2.2, it is clear that the proposed scheduling protocols are energy efficient and with high throughput. The energy efficiency comes from the synchronization of the sensor nodes to allow the sensor nodes to power off when it is not scheduled to send and receive. Such synchronized data transmission also eliminates the possibility for collision which has been identified as a major source of energy waste. The high throughput comes from the parallelism of the data transmission resulting directly from our explicit exploitation of the unique chain-type topology of such sensor networks. In addition, the proposed TDMA scheduling protocols also have the following characteristics.

Table 4
Code Channel (Bi-Direction)

Slot	Sender	
	Dir-1	Dir-2
0	0, 2, 4, 6, 8	
1	1, 3, 5, 7	
2		9, 7, 5, 3, 1
3		8, 6, 4, 2
4	2, 4, 6, 8, 0	

First, the above bidirectional scheduling scheme provides the fairness to the communications in both directions. In practical sensor network, there might be a predominant communication pattern, e.g., communications in direction-1 dominate over direction-2. In such case, more slots may be wasted in direction-2 communications. To remedy this, we can adjust the time allocations for unidirectional and bidirectional communications according to practical needs. For example, we can assign more frames to work in unidirectional communications, and less frames to work in bidirectional communications. The communication pattern of the current frame can be announced in the query broadcast period.

Second, as the unidirectional scheduling repeats the transmission pattern every 3 slots and the bidirectional scheduling repeats every 4 slots, we can design each frame to consist of $m \times 12$ slots, $m = 1, 2, \dots$. In this case, the exact frame length will depend on the network traffic load and latency requirement. Thus for a frame of 12 slots, the unidirectional scheduling will enable the sink nodes to receive 4 data packets, while the bidirectional scheduling will allow the sink nodes to receive 6 data packets in both directions.

Finally, in order to guarantee data delivery in MAC layer, an ACK packet should be returned from the receiver to the sender. Such mechanism will not cause collisions in the case of unidirectional scheduling. However, it may corrupt the data transmission in bidirectional scheduling using the frequency channel unless the data packets are of the same length. For example, in slot 0, node 4 is sending data to 5, node 3 is sending data to 2. If the data packet is of the same length, then the ACK packets will be successfully received by node 4 and 5 respectively. Otherwise, it may occur that when node 4 is receiving ACK, node 3 is still sending the data packet, thus ACK packet is corrupted at node 4. There are two possible solutions to this problem. The first solution is to confine the application of bidirectional scheduling to a fixed length data packet in a wireless sensor network. The second solution is to alternate the flow directions of the unidirectional scheduling. It is easy to see that the second solution offers flexibility at the cost of throughput degradation.

5.4. Performance Evaluation of Proposed MAC Protocol

As the protocols for networking and TDMA scheduling interact with each other intimately, we shall carry out one integrated simulation employing both networking and scheduling protocols. Two major indicators are important performance measures for the protocol evaluation: normalized energy consumption per bit of data transmission and aggregated throughput per node within the sensor network. For the last few years, there have been several energy efficient MAC protocols proposed for wireless sensor networks. In this research, we will compare the proposed scheduling protocols with SMAC, a well-known MAC protocol developed specifically for wireless sensor networks [2].

To carry out the simulations to evaluate the performance of the networking and scheduling protocols, we assume the cluster within a chain-type network shall have 10 nodes and therefore need 9 hops from one end to the other. Data load is generated at each node and varied by changing the data arrival rate. The simulation runs 100 frames for each data load. We use the energy model of Mica motes, the power consumptions of the radio in transmitting, receiving, and sleeping modes are 36 mW, 14.4 mW and 15 μ W respectively. Other important simulation parameters are listed in Table 5.

Slot length is no less than the transmission time of the maximum data packet and a control packet (ACK) as well as the maximum turn-around propagation time in the network.

Table 5
Simulation Parameters

Radio bandwidth	20 kbps
RTS/CTS/ACK packet length	10 bytes
Query packet length	30 bytes
Data packet length	0~200 bytes
Frame length	1.1s
Slot_id_max	12
Duty cycle of SMAC	1%~100%
Max. and Min. collision counter	6, 3
DIFS_Time	2 bytes

Thus for a 20 kbps radio bandwidth, the frame length is designed to be 1.1 s after considering all the above factors as well as the guard time. The overhead in the Synchronization period and the Joining period is assumed the same for both protocols and thus not considered in the simulation. In these simulations, the sensor data are not aggregated at any intermediate nodes in order to maximize the load on the MAC protocols. However, in practice, the sensor data are usually aggregated at intermediate nodes. Nevertheless, the performance of the networking and scheduling protocols will not be affected by whether or not a data aggregation scheme is implemented at the intermediate nodes.

Figure 11 demonstrates the energy efficiency of the proposed networking and scheduling protocols. The energy consumption per bit is obtained from the result of the total energy consumption of all nodes divided by the total bits successfully transmitted in the network. It shows that the proposed TDMA scheduling scheme outperforms the SMAC with duty-cycle 10% and 100% by about 27% and 40%, respectively. This is mainly because the TDMA scheduling scheme completely eliminates the collision and overhearing, and powers on the radio only when there is data to send or receive. In addition, it reduces the idle listening to a very low level by listening just DIFS_Time period (0.2 ms) in its scheduled receiving slot. Furthermore, it has less overhead than SMAC. For each successfully transmitted data packet, the scheduling scheme only induces ACK overhead and Query overhead. The Query overhead is imposed to all 12 slots of a frame and in each slot there are multiple parallel transmitted data packets. In contrast, SMAC will induce RTS/CTS/ACK overhead for each single data packet, and retransmissions caused by inherent collisions will lead to extra energy waste.

Figure 12 shows the throughput performance represented by the result of the total bytes successfully transmitted in the network divided by the total number of nodes. It demonstrates that the throughput of the proposed TDMA scheduling is about 15 and 1.5 times that of the SMAC with duty-cycle 10% and 100% respectively, while still maintaining higher energy efficiency as shown in Fig. 11. The throughput gain comes from its pipelining the maximum number of transmissions that do not interfere with each other because of chain-type topology. The gain also comes from collision-free transmission and reduced signaling overhead. When the duty-cycle of SMAC is less than 10%, the active period of a node is almost equal to or less than the time for transmitting a data packet length and therefore results in near zero throughput rates. The results for these cases are therefore not presented in Figs. 11 and 12.

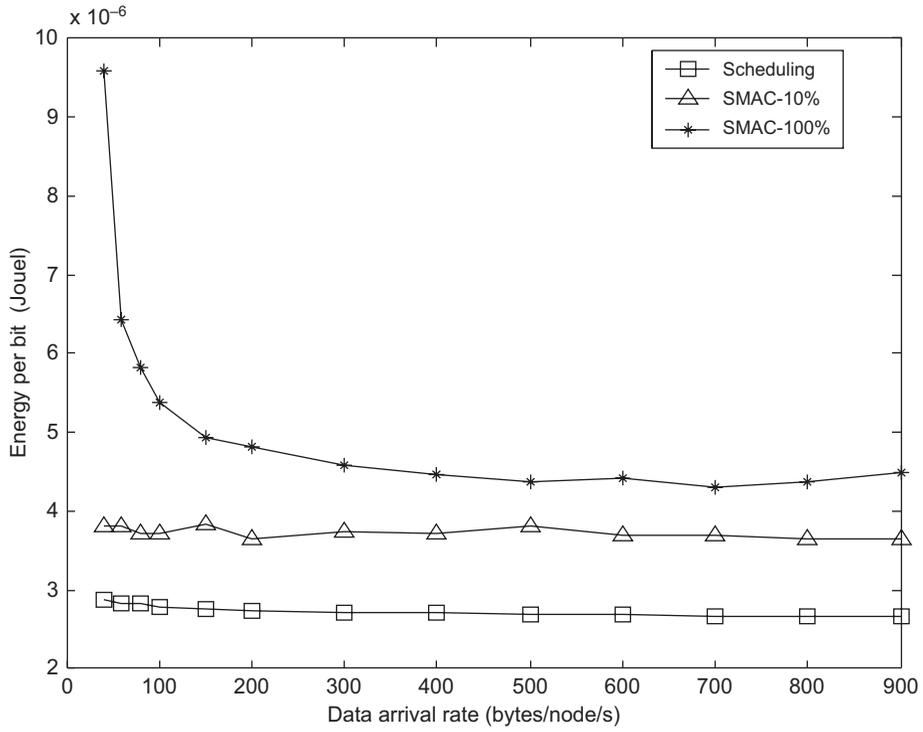


Figure 11. Energy consumption performance.

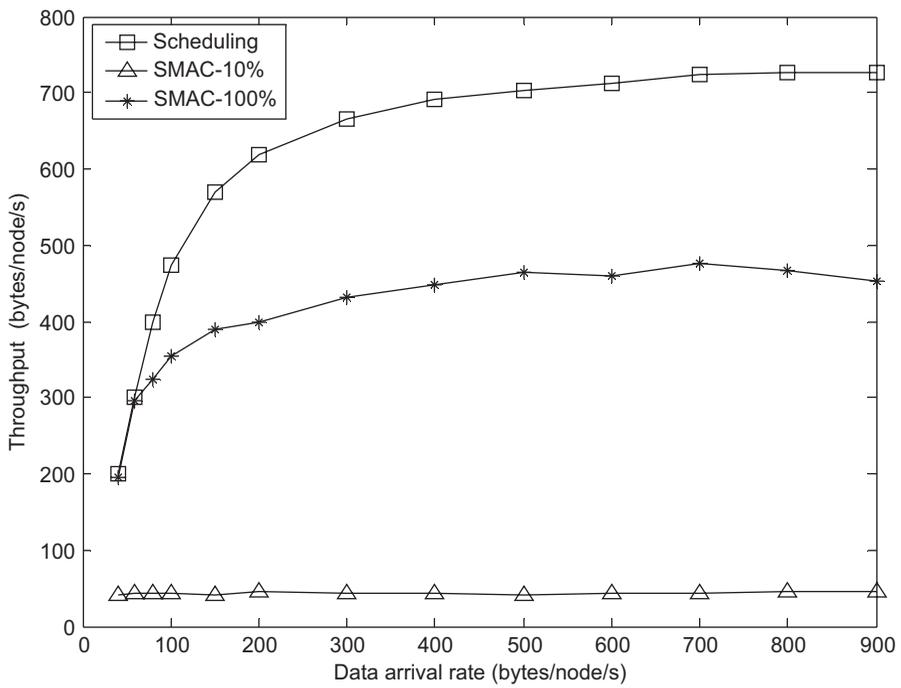


Figure 12. Aggregate throughput performance.

6. Summary and Discussion

We have presented in this paper the investigation of a special class of wireless sensor networks for monitoring critical infrastructures that may extend for hundreds of miles in distance. Such networks are fundamentally different from traditional sensor networks in that the sensor nodes in this class of networks are deployed along narrowly elongated geographical areas and form a chain-type topology. Based on careful analysis of existing sensor network architectures, we first demonstrate the needs to develop new architecture and networking protocols to match the unique topology of chain-type sensor networks. We then propose hierarchical network architecture that consists of multiple tiered clusters of sensor nodes to enable the chain-type sensor networks to be scalable to cover typically long range infrastructures with tolerable delay in network-wide data collection. To maintain energy efficient operations and maximize the lifetime for such a chain-type sensor network, we devise a smart strategy for the deployment of cluster heads. Protocols for network initialization and seamless operations of the chain-type sensor networks are also developed to match the proposed hierarchical architecture and cluster head deployment strategy. Simulations have been carried out to verify the performance of the hierarchical architecture, the smart node deployment strategy, and the corresponding network initialization and operation protocols.

We have also presented in this paper an energy efficient media access control (MAC) protocol for chain-type wireless sensor networks. The chain-type sensor networks are fundamentally different from traditional sensor networks in that the sensor nodes in this class of networks are deployed along narrow and elongated geographical areas and form a chain-type topology. In this paper, we developed novel TDMA scheduling protocols that take full advantages of the available channel reuse inherent in the chain-type sensor networks to develop energy efficient and high data throughput MAC protocols. The synchronized TDMA scheduling allows the nodes to power on only when it is scheduled to send and receive and therefore results in additional energy savings. Within a cluster, parallel transmission is made possible because of the linear distribution of nodes within the chain-type topology and this yields the desired high throughput. Preliminary simulations have been carried out to show that the proposed TDMA scheduling outperforms the well-known SMAC scheme in terms of energy efficiency and data throughput under various duty cycles.

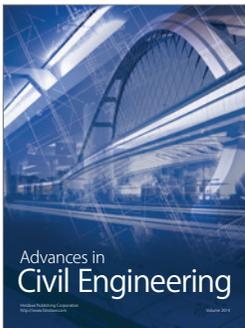
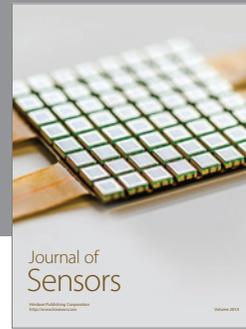
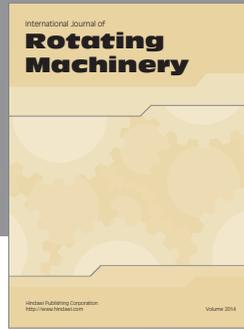
To develop a complete suite of protocols and algorithms for the chain-type sensor networks, appropriate data aggregation schemes also need to be developed. Data aggregation plays important roles in sensor networks since sensor data are inherently correlated due to sense deployment of the sensor nodes. Additional energy saving can be achieved with well designed data aggregation schemes. We are currently working on a unique data aggregation scheme specifically designed for the chain-type wireless sensor networks.

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