An Uncapacitated Facility Location Based Cluster Hierarchy Scheme on Wireless Sensor Networks

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Abstract: - Cluster-Head (CH) nodes function as gateways between the sensors and the Base Station, in Wireless Sensor Networks with a cluster hierarchy. The total energy dissipation of the sensors can be reduced by optimizing the load balance within the cluster hierarchy. This paper proposes an uncapacitated facility location based cluster scheme in which the system lifetime is extended by adding an additional layer of Super-Cluster-Head (SCH) nodes, in order to ease the transmission load of the CHs and to balance the load distribution within the network. The SCH layer is configured using an uncapacitated facility location algorithm in which the facility and service costs are defined in terms of both the energy and the transmission distance. The simulation results confirm that the proposed method yields a better load balance in the SCH layer than that obtained using either a random configuration or a round-robin scheme. Finally, it is shown that irrespective of the size of the sensor field, the proposed scheme outperforms the conventional LEACH-C two-layer scheme in terms of the average energy dissipation of the nodes, the average survival times of the nodes, and the overall system lifetime.

Key-Words: - Wireless Sensor Network, Gateway Node, Cluster hierarchy, Uncapacitated Facility Location Problem

1 Introduction

As wireless technology and miniaturized fabrication technologies have matured in recent decades, these so-called wireless sensor networks (WSNs) have been increasingly deployed for a variety of applications, ranging from environmental monitoring, to battlefield surveillance, disease detection, animal migration, traffic or tank truck transportation [1] monitoring, and so forth. In WSNs, a large number of sensors are densely deployed within an environment of interest and used to report changes in this environment over time to a central base station (BS).

In general, the sensors are small, low-cost devices with limited data processing, computing and broadcasting capabilities [2]. The sensors are energy-constrained in that they are battery operated and it is generally impossible to replace the batteries once their energy has been fully consumed [3]. The energy dissipated by the sensors in transmitting data is far greater than that consumed in performing basic data processing tasks. And the sensors are easily damaged since they are typically deployed for extended periods in an outdoor or hostile environment. Without sufficient coverage (i.e. sensor redundancy), the failure of a single sensor, or the presence of unexpected noise, may result in significant events passing unnoticed in the sensor field. While the topologies of most WSNs are stationary or change only slowly [4], those of certain applications such as animal migration tracking, plants growing monitoring, and real-time detection for patients' status, for example, change on a frequent basis due to the movement of the individual sensors.

In networks such as those described above, the energy consumed by the nodes depends on the frequency at which they transmit and the distance over which they broadcast this data. As a result, the energy is rapidly consumed if the nodes are located at too great a distance from the BS or are required to communicate on too frequent a basis with the BS. Furthermore, the effects of data distortion and noise also increase as the transmission distance increases.

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Thus, optimizing the network configuration is essential to maximizing the system lifetime whilst simultaneously ensuring full data connectivity and coverage within the network. In an attempt to satisfy this requirement, WSNs are frequently configured using a cluster hierarchy, in which the sensors within a particular region of the sensor field report their information to a central node (designated as a Cluster-Head (CH) node), which then aggregates this information and transmits it to the BS.

The presence of the CHs shortens the distance over which the individual sensors are required to transmit their data, and therefore reduces their energy consumption. Furthermore, the CHs pre-process the data received from the sensors by removing redundant, aggregating data, in order to reduce the volume of the transmitted data. This not only reduces the energy required to broadcast the sensor information to the BS, but also accelerates the data transmission process [2][5].

The discussions above imply that the energy dissipation, transmission speed and system lifetime can all be improved via an appropriate configuration of the CH gateway nodes. In a recent study, Santi [4] confirmed that the energy consumption in a WSN could be significantly reduced through the implementation of an appropriate topology control mechanism. Accordingly, this study proposes a three-layer cluster hierarchy scheme for WSNs, in which an additional layer of nodes, designated as Super-Cluster-Head (SCH) nodes, is introduced between the CHs and the BS. The SCH selection is formulated as an uncapacitated facility location problem (UFLP) and is solved in such a way as to minimize the energy consumed during the CH-to-SCH-to-BS transmission process in order to optimize the system lifetime. In addition, the proposed scheme applies an energy-efficient clustering scheme “a simulated annealing method” to optimize both the number and the positions of the CHs in response to changes in the availability and positions of the sensors within the network.

Overall, the introduction of the additional SCH layer enables the processing/transmission load to be balanced across all the nodes in the network on an adaptive basis and reduces the number of redundant data transmissions. As a result, the three-layer cluster hierarchy yields an effective reduction in the energy consumed and therefore achieves a significant improvement in the system lifetime.

The remainder of this paper is organized as follows. Section 2 reviews the related research. Section 3 describes the three-layer cluster hierarchy scheme proposed in this study, while Section 4 discusses the use of the UFLP algorithm in configuring the SCH layer. Section 5 analyzes the total energy expenditure of a three-layer network and compares this cost with that of a two-layer hierarchy with equivalent network parameters. Section 6 performs a series of simulations to benchmark the performance of the proposed three-layer cluster hierarchy scheme against that of the LEACH-C two-layer clustering scheme [6] and to evaluate the performance of the UFLP algorithm in configuring the SCH layer. Finally, Section 7 summarizes the major contributions of the present study and provides some brief concluding remarks.

2 Related Work

The cluster hierarchy is an effective approach for achieving high levels of energy efficiency and scalability, which is widely regarded as an optimal solution for WSN implementations [7][8]. Most cluster hierarchies consist of just two layers, i.e. a lower layer of sensors and an upper layer of CHs. Through a careful selection of the CHs, this two-layer structure can achieve the dual goals of minimizing the energy dissipation and obtaining a uniform load balance. Heinzelman et al. [6] showed that the use of pre-configured routing paths in cluster-based topologies improved the resource allocation, minimized the total energy expenditure, and allowed for bandwidth reuse in the transmission process.

Clustering techniques are used to organize sensors with one selected CH in each cluster. Iranli et al. [9] developed energy-efficient strategies for resolving MEDA (Micro-server Deployment and Energy Allocation) problem in two-level WSNs. This method clustered sensors and identified the presentation of each cluster with the CH by data mining technique. The approach can find CHs, but could not decide the applicable number of CHs, and are only for static WSNs. Tillett et al. [10] used PSO (Particle Swarm Optimization) technique to cluster the sensors into clusters of equal size based upon the criterion that each CH expended an approximately equal amount of energy in performing its data receiving and pre-processing tasks. The simulation results showed that the proposed approach successfully balanced the load of each cluster. However, the method is unable to determine the optimal number of CHs, and is inapplicable to dynamic networks or to networks in which the sensor density varied greatly from one region to another. Jin et al. [11] considered static WSNs and utilized a genetic algorithm to cluster the sensors using a fitness function based upon the transmission distance. Although this method successfully determines the total number of CHs required and identified suitable gateway nodes, the fitness function is overly simplistic.

In conventional WSNs, the CHs used to perform a gateway function are simply chosen from amongst the sensors deployed in the network in accordance with their location or some other characteristic. They are physically no different from any of the other sensors, and are therefore also energy-constrained. In theory, once, the CH has consumed all its energy, all of the sensors within its group lose their ability to communicate with the BS. Accordingly, various researchers have proposed schemes for conserving the energy resources of CH devices by rotating the CH function between the different sensors in a group in order to balance the load. For example, Culpepper et al. [12] rotated the CH function by selecting other sensors in accordance with certain criterion.

Moussaoui and Naïmi [13] proposed DECHP (Distributed Energy-efficient Cluster hierarchy Protocol) consisting of two phases, namely a setup phase and a data communication phase. In the setup phase, the sensors identified their neighbors and formed themselves into a set of clusters. The sensor within each cluster having the greatest remaining energy was then elected as the CH for that group. Once a CH had been selected in every cluster, each CH selected an intermediary CH between itself and the BS for transmission purposes in accordance with the total distance to the BS and the remaining energy of the target CH. During the data communication phase, each CH forwarded the data sensed within its cluster to the target CH, which in turn forwarded this data, together with its own, to the BS. In this phase, each CH monitored the average remaining energy within its cluster and scheduled the transmissions of the individual member sensors using TDMA (Time Division Multiple Access) protocol in order to reduce transmission collisions. If the remaining energy of the CH fell below the average remaining energy within the cluster, the sensor having the highest remaining energy within the cluster was automatically designated as the new CH. Whilst this two-phase method enables suitable CHs to be identified, it cannot determine the optimal number of CHs required. Nor is it applicable to dynamic WSNs. Furthermore, the CHs experience a heavy load since they are required not only to act as cluster heads in aggregating and consolidating the data received from the sensors within their group and transmitting this data to the BS, but also to play the role of intermediary broadcasting stations in forwarding the data received from other CHs toward the BS.

As the load of CHs is too heavy to afford data processing and the far transmission to the BS, Nam and Min [14] proposed RRCH (Round-Robin Cluster Header) method that fixed the cluster and selected the CH in a round-robin method The RRCH approach is an energy-efficient method that realizes consistent and balanced energy consumption in each node of a generated cluster to prevent repetitious setup processes as in the LEACH method.

Heinzelman et al. [15] proposed a clustering scheme designated as LEACH (Low-Energy Adaptive Cluster hierarchy) in which an initial set of CHs were randomly chosen and a self-organization procedure was then performed to adaptively construct sensor clusters and to rotate the CHs in such a way as to evenly distribute the energy load amongst the sensors. Heinzelman et al. [6] later proposed an improved clustering scheme, designated as LEACH-C (Low-Energy Adaptive Cluster hierarchy - Centralized), in which rather than selecting the CHs on a random basis, the BS applied a simulated annealing algorithm based on a global knowledge of the energy capacities and locations of all the sensors to establish the optimal cluster formation and to select appropriate CHs.

The principal advantages of LEACH-C include high energy-efficiency and a uniform load balance. The power efficiency arises as a result of the use of CHs, which shortens the transmission distances of the individual sensors and allows for a reduction in the volume of the transmitted data. In addition, the CHs schedule the sensor transmissions using a TDMA scheduling approach which reduces the occurrence of transmission collisions and therefore limits the requirement to retransmit the data. Meanwhile, the improved load balance is achieved primarily by rescheduling the CH function amongst the sensors on a periodic basis.

However, since the CHs are selected from amongst the original sensors and are required to transmit data directly to the BS, LEACH-C makes the fundamental assumption that all the nodes have sufficient energy to transmit as far as the BS. However, this assumption does not generally hold in real-world networks, in which the BS is commonly located far from the sensor field. In addition, the use of the transmission distance as the sole criterion in determining the optimal clustering configuration and selection of CH devices is too simplistic since shorter transmission distance to the BS might consume more energy due to barricades.

The uncapacitated facility location problem [16] involves optimizing the set of service facilities provided to a large number of cities, where each facility is associated with a certain cost and the provision of this service to each city also has a particular cost. The overall objective of the UFLP problem is to determine the subset of all the service facilities associated with each city which minimizes the total overall cost. Krivitski et al. [5] solved the UFLP problem in WSNs by using the Hill Climbing method and treating the transmission distance and the relative importance of the transmitted data as the main cost factors. In their study, the objective was to select *k* CHs from amongst a set of *m* stationary CHs, and the authors assumed that the optimal number of CHs could be specified in advance, which may not in fact be possible in real-world networks since sensors' status is changed and the number of senor might shift with time.

Furuta et al. [17] proposed a clustering algorithm based on facility location theory for optimizing the topologies of static WSNs. In the proposed approach, the transmitting and receiving energies of the nodes were treated as the primary cost factors. The results showed that the clustering algorithm was capable of optimizing both the number and the position of the CHs. However, the CH function was still performed by "normal" sensors (e.g. MICA2 [18] from Crossbow), and thus the energy capacity of these nodes was rapidly depleted, leading to a short lifetime.

3 System Architecture and Flowchart

Despite the contributions of the cluster-based schemes discussed above, they commonly impose assumptions which do not actually hold true in practical networks. For example, the schemes frequently assume the nodes to be deployed in a stationary network and to have sufficient energy to connect directly to the BS. By contrast, in certain practical networks, the sensors are actually mobile (e.g. sensors used to trace the migrational habits of animals) and have insufficient energy to broadcast as far as the BS. Moreover, many of the schemes lack the ability to dynamically adjust the number of CHs in a WSN in accordance with changes in the network conditions or to optimize their locations.

As described earlier, conventional cluster-based WSNs generally have a two-layer topology, in which the first layer comprises sensors designed to detect events within the field of interest, and the second layer consists of CHs, selected from amongst these sensors and designed to aggregate the sensed data and send it to the BS. However, in typical WSNs, the BS is located far from the sensor field, and thus the energy resources of the CHs are rapidly consumed. Even though many methods attempt to resolve this problem by rotating the CH function amongst the sensors, the effectiveness of such schemes is inevitably limited since the CHs are simply normal sensors with limited battery capacity. Even if one adopts the policy of deploying special sensors with enhanced computational and energy resources as CHs, it is still difficult to predict the appropriate number and locations of these nodes in networks characterized by large numbers of movable sensors. Furthermore, in some environments, e.g. battlefields, disaster areas, or jungles, it is physically impossible to gain access to the sensor field to position these sensors in their appropriate locations even if these locations can be ascertained. Finally, whilst positioning these special sensors around the periphery of the sensor field resolves the problem of gaining access to the sensed environment, the normal sensors within the sensor field are then required to transmit their information over a greater distance, and therefore consume their energy resources more rapidly, leading to an early failure of the network.

The discussions in the remainder of this section review the proposed scheme and present a flowchart showing the major phases. The detailed algorithms used to cluster the sensors and to configure the SCH layer are then presented in Section 4.

3.1 System Architecture

In summary, no matter that the CHs are normal or special sensors, the two-layer cluster hierarchy is not suitable for the dynamic WSNs with the BS being far away from the surveillance environment. Thus, our goal is to design a suitable hierarchy, which can reduce CHs transmission load, prolong system lifetime, and handle movable sensors. In mobile ad hoc networks (MANETs), hierarchical clustering hierarchies can be used to prolong the network's lifetime [19][20][21], attain load balancing [22], and increase network scalability [6] [23][24]. So, adding layers to the cluster hierarchy is an intuitive solution. But raising more layers will increase system complexity and cost, and it will not help in prolonging lifetime because the bottleneck of lifetime is on the energy capacity of sensors.

Accordingly, this study proposes an energy-efficient three-layer cluster hierarchy scheme which retains the advantages of a traditional two-layer cluster-based WSN (namely an improved load balance and a better energy consumption), but gains a further power efficiency improvement through the deployment of an additional set of SCH nodes, between the CHs and the BS. The proposed scheme

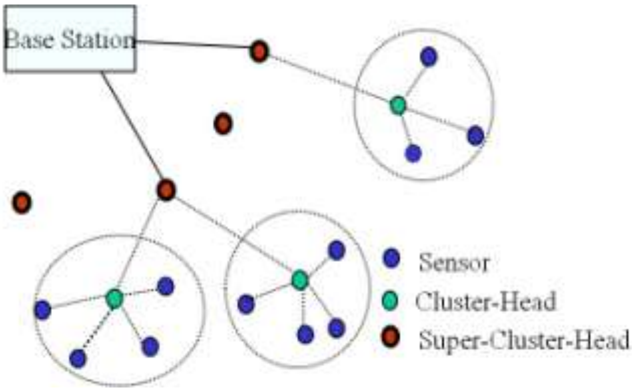

Fig. 1. Energy-efficient three-layer cluster hierarchy.

focuses specifically on dynamic rather than static networks and determines both the appropriate number and the energy-efficient location of the CHs in accordance with the changing states and positions of the sensors. The clustering and CH nomination process is performed by the BS using a simulated annealing algorithm, while the configuration of the SCH layer is optimized using an UFLP algorithm in which the CHs are regarded as cities and the SCHs as facilities. The performance of the proposed three-layer cluster hierarchy scheme and the effectiveness of the UFLP configuration mechanism are evaluated by performing a series of simulation.

Various researchers [5][9][25] have used special gateway nodes to cache and forward compressed data to the BS in order to improve the performance, throughput, reliability, longevity and flexibility of the system [9]. For example, Tseng et al. [25] utilized enhanced mobile sensors as to serve as gateways in the proposed iMouse system. In addition to supporting the CHs, the SCHs also serve as distributed processors within the WSN and decentralize the load imposed on the BS, e.g. by performing a local data mining function, a local controller, and so forth. The SCHs perform a similar role to the Tmote Connect Gateway Appliances marketed by Sentilla (formerly Moteiv Corporation [26]) in improving the transmission performance by aggregating or compressing the data transmitted from the CHs to the BS. Thus, although the SCHs are more expensive than the other nodes in the WSN due to their greater bandwidth, computational and transmission capabilities, this cost is offset by the benefit which their deployment brings in terms of overcoming the limitations associated with conventional two-layer WSN hierarchies.

Fig. 1 illustrates the proposed three-layer WSN hierarchy. As shown, the first (i.e. lowest) layer consists of dynamic normal sensors which sense events or capture data from the local environment and send this information to the CHs in the second layer. The CHs accumulate, pre-process and aggregate the received information and then send it to the SCHs within the third layer. Finally, the SCHs compress the data received from the CH(s) and then transmit it to the remote BS.

One of the major advantages of the proposed three-layer hierarchy is the ability it provides to deploy large-scale networks in hostile or impenetrable environments such as battlefields, jungles, and so forth. Tanenbaum et al. [27] pointed out that while researchers have proposed many solutions for network problems which yield promising results when evaluated using lab-based simulations, efforts to move these solutions into the real world have proven less successful. The authors argued that WSNs based on simple, low-cost sensors with homogenous computational and energy resources could only be effectively deployed on a limited scale since the large-scale deployment of such sensors (by dropping the sensors from the air, for example) would be unlikely to result in an efficient, operational WSN; particularly if the BS was located far from the sensor field. By contrast, in the three-layer hierarchy proposed in the current study, these sensors are supported by enhanced-capacity SCHs which relay their information to the BS. Thus, a sensing capability can be easily obtained by distributing low-cost sensors randomly throughout the sensor field (i.e. via an air drop) and then manually positioning a small number of enhanced-capacity SCHs either within the sensor field if access can be gained, or around the periphery of the sensor field if it cannot.

3.2 SCH Layer

In modeling a dynamic WSN using the proposed three-layer scheme, an assumption is made that the BS is located far from the sensor field. Furthermore, it is assumed that the BS knows the location and remaining energy of every node within the network. Finally, each sensor is assumed to have the ability to connect directly to the SCHs and to move randomly within the sensed area.

In deploying the SCH layer, it is assumed that the individual SCH devices are positioned manually in or around the sensor field in advance, to be closer to the BS than CHs or normal sensors. As described earlier, the SCHs have multiple roles, including local data mining, consolidating the data received from the CHs, transmitting this data to the BS, and so forth. Hence, each SCH is deliberately assigned greater bandwidth and energy capacity than the CHs or sensors, in order to prolong the overall lifetime. So, having deployed the SCHs, the UFLP algorithm

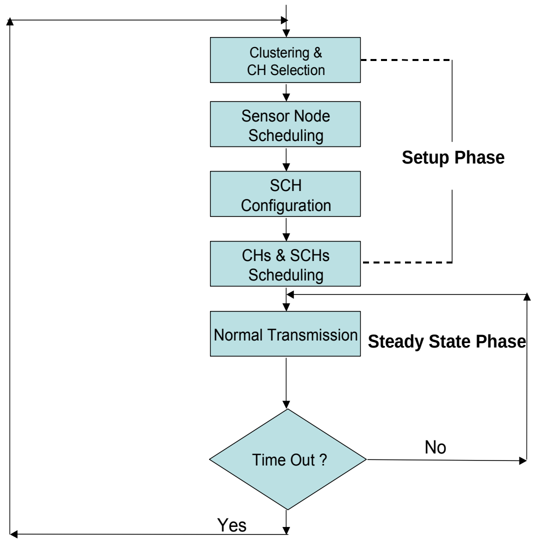

Fig. 2. Flowchart showing major modules in proposed energy-efficient three-layer cluster hierarchy.

is used to configure the SCH layer by selecting certain of the deployed SCHs while deactivating the remainder in order to conserve their energy resources.

3.3 System Flowchart

In the initialization stage of the proposed scheme, a large number of sensors are randomly deployed within the surveillance area and a small number of SCHs are uniformly distributed within the sensor field or around its perimeter. As shown in Fig. 2, the proposed scheme comprises two discrete phases, namely the setup phase and the steady state phase. The detailed mechanisms of these two phases are described in the following sections.

3.3.1 Setup Phase

The setup phase comprises four modules, namely (1) Clustering & CH Selection module, (2) Sensor Node Scheduling module, (3) SCH Configuration module, and (4) CH & SCH Scheduling module.

(1) Clustering & CH Selection Module

Since the sensors are initially deployed in a random fashion, the BS executes a clustering routine to group the sensors into clusters and to select an appropriate CH within each cluster. (The details of the Clustering and CH Selection algorithm are presented in Section 4.1.)

(2) Sensor Node Scheduling Module

The CHs schedule the transmissions of the sensors within each cluster using the TDMA protocol as in LEACH-C [6]. Each sensor is allocated a unique time frame within which to transmit its data to the CH. This scheduling approach not only reduces the risk of data collisions, but also enables a significant energy saving to be obtained by deactivating the radio modules of all those sensors which are not currently scheduled to transmit.

(3) SCH Configuration Module

As described above, the SCHs are uniformly distributed during the initialization stage. We formulate the SCH configuration problem as an UFLP problem [16]. Having configured the clusters within the sensor field and nominated the CHs, the BS then applies the UFLP algorithm to select an appropriate SCH for each CH. Having identified and activated suitable SCHs, the remaining SCH devices are put to sleep in order to conserve their energy resources. (The details of the UFLP algorithm are presented in Section 4.2.)

(4) CH & SCH Scheduling Module

As in the Sensor Node Scheduling Module, each active SCH schedules the transmissions of the CHs connected to it using a TDMA policy. Similarly, the transmissions of the SCHs to the BS are also scheduled by the BS using a TDMA approach. As with the lowest-level sensors and the CHs, any nominally active SCHs which are not currently scheduled to transmit to the BS are placed in a sleep mode to conserve their resources.

Having configured the three-layer cluster hierarchy using these four modules, the network enters the steady state phase, as described in the following.

3.3.2 Steady State Phase

In the steady state phase, the WSN senses and transmits data continuously until a predefined time-out parameter expires. The expiry of this parameter signals the end of one complete operational round of the WSN and prompts the cluster hierarchy scheme to return to the first module in the setup phase.

In the Normal Transmission module of the steady state phase, the sensed data is routed in accordance with the routing paths constructed in the setup phase. Once the time-out parameter expires, the Normal Transmission module terminates, and the WSN is re-clustered and reconfigured using the four modules in the setup phase. During this procedure, any CHs or SCHs found to be dysfunctional are automatically excluded from the clustering and CH/SCH nomination routines.

By adopting the cyclic setup/steady state policy shown in Fig. 2, the three-layer hierarchy can be continuously reconfigured to balance the load within each layer and to reflect changes in the network topology caused either by the change in state of the various nodes within the network or by movements of the sensors in the second and third layers of the network.

Clearly, the value assigned to the time-out parameter must be sufficient to enable each of the nodes within the network to send their data to the BS at least once. In other words, the time-out parameter is application dependent. A shorter time-out parameter implies that the system will be reconfigured more frequently, and is therefore more responsive to changes in the sensors' states and locations. However, the re-clustering and reconfiguration tasks inevitably incur a computational overhead at the BS. In large-scale WSNs, this overhead can be substantial. Thus, in practice, when specifying the value of the time-out parameter, a trade-off must be made between optimizing the network topology and minimizing the computational overheads incurred in the reconfiguration process.

4 The Uncapacitated Facility Location Based Cluster hierarchy Scheme

As shown in Fig. 2, implementing the three-layer cluster hierarchy involves solving two main problems, namely the Clustering & CH Selection problem in the first module and the SCH Configuration problem in the third module. The algorithms used in this study to solve these two problems are described in the following sections.

4.1 Clustering & CH Selection Problem

The aim of the Clustering and CH Selection problem is to identify both the appropriate number of CHs required to support the network and to select suitable sensors to perform the CH function.

Since the main function of the CHs is to gather, aggregate and transmit data to the SCHs, the manner in which the clusters are formed and the CHs are selected has a direct impact upon the energy dissipation characteristics of the entire network. LEACH-C is specifically designed to cluster the sensors and to select suitable CHs in such a way as to minimize the energy consumption and to obtain a uniform load balance. To enable a fair comparison to be made between the performance of the current three-layer cluster hierarchy scheme and that of a two-layer cluster hierarchy scheme such as LEACH-C, LEACH-C is deliberately adopted in the present study to solve the Clustering & CH Selection problem in the first module of the setup phase.

In LEACH-C, each sensor sends its current position and remaining energy level to the BS. A sensor can get its location at low cost from GPS or some localization systems [28]. The problem of selecting the *k* appropriate clusters from amongst all these nodes is an NP-hard problem and is solved by the BS using a simulated annealing algorithm. Having arranged the sensors into clusters, the BS calculates the average remaining energy of the sensors within each cluster and selects the CH from amongst the individual sensors having a remaining energy greater than the average energy value. Having identified the energy-efficient clusters within the WSN and selected the CHs, the BS transmits the results to all the sensors.

4.2 SCH Configuration Problem

Once the sensors have been clustered and suitable CHs selected, the BS configures the nodes in the SCH layer. If each CH were implied connected to the nearest SCH, the SCH devices would be unevenly loaded and thus the overall system lifetime would be degraded. Therefore, in the proposed scheme, the SCH configuration problem is treated as an UFLP problem, in which a sub-set *k* of the total of *m* deployed SCHs are selected as active SCHs. The overall objective of the UFLP is to minimize the total energy dissipation of the CHs and the SCHs and to balance the load in the SCH layer. As described earlier, the selected SCHs are then activated, while the remainders are put to sleep to conserve their energy. Note that the capacity of each SCH is not considered in the UFLP algorithm since a CH may connect to a far SCH due to SCH's capacity limitation and result in more energy consumption.

The principal objective of the SCHs is to reduce the transmission burden imposed on the CHs. According to Krivitski et al. [5], however, the use of a transmission distance criterion alone is insufficient to configure the nodes within a WSN. In other words, it is also necessary to take account of the remaining energy available at each node. Heinzelman et al. [15] and Santi [4] argued that the total transmission energy between two nodes in a WSN comprises the individual energies expended by the sender and the receiver, respectively. In practice, however, the energy dissipated by the receiving node is far smaller than that consumed by the transmitting node, and thus to all intents and purposes, the energy dissipation at the receiving node can be effectively ignored. In using the UFLP algorithm to solve the SCH configuration problem, this section commences by defining appropriate facility cost and service cost functions based upon the dual criteria of the transmission distance and the remaining energy available at each node, respectively. Each CH and SCH in the WSN is then assigned two quantities, namely a transmission energy and a remaining energy. Having done so, a cost function is applied to select k SCHs out of the m deployed SCHs. That is, only k SCHs are activated, and other (m-k) SCHs are in sleep mode during the steady state phase. Note that in doing so, the value of k is not known in advance. It is dynamically determined through solving the UFLP using real-time system status.

Definition 1: Facility Cost
The facility cost of each SCH j is defined as e_{jBS}/e_j, where e_{jBS} indicates the transmission energy expended by SCH j in transmitting to the BS and e_j indicates the remaining energy of SCH j. In other words, e_{jBS}/e_j provides an indication of the impact on the remaining energy of the SCH in making a single transmission to the BS.

A high facility cost implies that the SCH will consume a significant amount of its remaining energy in transmitting data to the BS, and therefore this SCH is viewed less favorably when selecting SCHs for activation purposes. However, as the operational lifetime of the WSN increases, the facility costs of the SCHs invariably increase since all of the SCHs are likely to have been selected for activation in one (or more) of the previous operational rounds and will therefore have consumed some of their original energy resources.

Definition 2: Service Cost
The service cost between CH i and SCH j is defined as e_{ij}/e_i, where e_{ij} indicates the transmission energy expended by CH i in transmitting to SCH j and e_i indicates the remaining energy of CH i.

By considering both the facility costs of the SCHs and the service costs of the CHs, a better balance can be found which reduces the total energy dissipation. However, in configuring the SCH layer, the aim is not only to minimize the energy dissipation within the network, but also to achieve a uniform load balance. Therefore, the facility cost and service cost functions defined above deliberately take into account the impact of the transmission distance on the remaining energy of the node. This strategy ensures a more uniform load balance than that achieved using cost functions based on the average remaining energy alone. That is, if the SCHs were selected for activation purposes simply on the basis of their average remaining energy, SCHs with a higher remaining energy level would always be chosen in preference to SCHs with a lower remaining energy level. This results in a non-uniform load balance since SCHs with higher energy resources are repeatedly selected in each operational round, while those with lower remaining resources are ignored even if they are closer to the BS and will therefore consume less transmission energy. By contrast, the UFLP configuration algorithm applied in the proposed SCH configuration procedure favors a low facility cost when selecting SCH nodes for activation purposes even if the remaining energy levels of these nodes are not the highest amongst all the SCH devices. Thus, a more uniform distribution of the load is obtained. The load uniformity is further improved within the SCH layer since the relative favor of a particular SCH decreases as its energy is consumed (i.e. its facility cost increases). As a result, the UFLP configuration scheme selects only those SCHs whose remaining energy resources are larger than the average remaining energy of all the SCHs.

Definition 3: candidate SCHs
SCHs whose remaining energy resources are larger than the average remaining energy of all the SCHs.

Definition 4: SCH Configuration Problem
The SCH configuration problem is to find a configuration with the proper number and positions of candidate SCHs and to determine the connections from CHs to these selected SCHs subject to one CH connected to exactly one candidate SCH.

Assume that a set with m candidate SCHs is designated as *CSCHSet*, and a set with n CHs is denoted as *CHSet*. Let $CSCHCost_j$ ($1 \le j \le m$) be the facility cost of candidate SCH j, and $SRVCost_{ji}$ ($1\le i \le n$, $1 \le j \le m$) is the service cost from CH i to candidate SCH j. The goal is to find an SCH configuration which can minimize the sum of the facility cost and the service cost to obtain most efficient energy conserving and balance the load within the SCH layer. The objective function is:

$$\min\left(\sum_{j=1}^{m}\sum_{i=1}^{n}\mathrm{SRVCost}_{ji}x_{ji} + \sum_{j=1}^{m}\mathrm{CSCHCost}_{j}\cdot y_{j}\right) \qquad (1)$$

subject to:

$\sum_{j=1}^{m} x_{ji} = 1,$ $\quad x_{ji}\in\{0,1\}$, for every $i\in CHSet$;

$0 \le x_{ji} \le y_j$ and $y_j\in\{0,1\}$, for every $j\in CSCHSet$ and every $i\in CHSet$. y_j indicates whether candidate SCH j is selected (y_j=1) or not (y_j=0). x_{ji} represents whether or not CH i is served by candidate SCH j in the solution. That is, each CH can connect to exactly one candidate SCH only.

Solving the SCH configuration problem using the UFLP algorithm is an NP-hard problem and is solved in this study using the combinatorial approximation algorithm presented in [16]. The algorithm is based on a greedy local search method, which starts from an initial solution and repeatedly attempts to improve the current solution by performing local search operations. The detailed processing steps in this algorithm are shown below:

Notations:

- SCHSet is the set of all SCHs.
- ê is the average remaining energy of all SCHs.
- CSCHSet is the set of candidate SCHs whose remaining energy is larger than ê.
- CHSet is the set of all CHs.
- $CSCHCost_j$ is the facility cost of candidate SCH *j* and is set to e_{jBS} / e_j, where e_{jBS} is the transmit energy from candidate SCH *j* to BS, and e_j is remaining energy of candidate SCH *j*.
- $SRVCost_{ji}$ is the service cost of CH *i* to candidate SCH *j* and is set to e_{ij} / e_i, where e_{ij} is the transmit energy from CH *i* to candidate SCH *j*, and e_i is remaining energy of CH *i*.
- TCSCHCost is the total facility cost of candidate SCHs and TSRVCost is the total service cost of a solution.

SCH Configuration Algorithm

Input:

SCHSet, CHSet, ê, the position and remaining energy of each SCH, the position of each CH.

Output:

A subset of CSCHSet in which each CH connects to exactly one candidate SCH, and TCSCHCost + TSRVCost is minimum.

Method:

1 Find CSCHSet from SCHSet.

2 The initial solution is generated as follows.

2.1 Candidate SCHs in *CSCHSet* are sorted in increasing order by facility cost.

2.2 Let $TCSCHCost_p$ be the total facility cost and $TSRVCost_p$ be the total service cost for the solution consisting of the first *p* candidate SCHs in this order. We compute the $TCSCHCost_p$ and $TSRVCost_p$ values for all *p* and choose the solution that minimizes $TCSCHCost_p$ + $TSRVCost_p$ in an incremental fashion as follows.

2.2.1 Examine each CH *i*, and compare its current service cost to the new candidate SCH. If it is cheaper to connect CH *i* to the new candidate SCH, we do so.

2.3 Let the total cost of the current solution be *TCSCHCost* + *TSRVCost*.

3 Improve the current solution.

Let *CSCHTemp* be the set of candidate SCHs in the current solution, *SRVCost*_gain(*j'*) be the gain of service cost by introducing candidate SCH *j'* in the improvement solution, and CSCHCost_gain(*j'*) be the gain of facility cost by introducing candidate SCH *j'* in the improvement solution. Let gain(*j'*) be the gain of total cost by introducing candidate SCH *j'* in the improvement solution, *D(j)* be the set of CHs assigned to candidate SCH *j* after marked CHs being reassigned.

3.1 For each candidate SCH $j' \not\in$ CSCHTemp

gain(*j'*)=0

3.1.1 Let d(*i*) be the candidate SCH in CSCHTemp assigned to CH *i*.

3.1.1.1 If the $SRVCost_{j'i}$ is less than the current service cost of CH *i*, mark CH *i* for reassignment to candidate SCH *j'*. ($SRVCost_{j'i} < SRVCost_{d(i)i}$)

$$SRVCost\_gain(j') = \sum_{i \in \text{CHSet}} (SRVCost_{d(i)i} - SRVCost_{j'i})$$

3.1.1.2 We also mark candidate SCHs whose CHs have been marked for reassignment to candidate SCH *j'*. Let *MarkedSCH* be the set of these marked candidate SCHs.

3.1.2 Let *j* be the currently considered candidate SCH in CSCHTemp. As some of CHs are currently assigned to candidate SCH *j* may have already been marked for reassignment to candidate SCH *j'*. Consider the change in cost if all these CHs are reassigned to candidate SCH *j'* and such candidate SCH *j* removed from the current solution.

For each $j \in MarkedSCH$ and *D(j)* is empty

$$CSCHCost\_gain(j') = \sum_{j \in MarkedSCH} CSCHCost_j - CSCHCost_{j'}$$

3.1.3 gain(*j'*)=*SRVCost*_gain(*j'*)+CSCHC*ost*_gain(*j'*)

3.1.4 If gain(*j'*) > 0,

3.1.4.1 Incorporate candidate SCH *j'* into the current solution.

3.1.4.2 For each marked CH *i*

If d(*i*)∈*MarkedSCH* and *D*(d(*i*)) is empty then marked CHs are reassigned to candidate SCH *j'*, and candidate SCH d(*i*) is removed. *TCSCHCost* + *TSRVCost* decreases by gain(*j'*).

3.1.4.3 *CSCHTemp* is the new set of candidate SCHs in the current solution.

Lemma 1: *The time complexity of the SCH Configuration Algorithm is O(m*n), where m is the number of candidate SCHs and n is the number of CHs.*

Proof. In the initial solution step: Sorting candidate SCHs takes O(*mlogm*) time. Calculating the cost of initial candidate solutions in an incremental way is shown in line 2.2 and line 2.2.1. The cost of the solution with the first *p* candidate SCHs in sorted order is computed, where 1≤ *p*≤ m. That is, for each candidate SCH, we examine each CH *i*, and compare its current service cost to the new candidate SCH. If it is cheaper to connect *i* to the new candidate SCH, we do so. Because 1≤ *i* ≤ *n*, which takes O(*m*n*) time.

Before proving the time complexity of the improvement solution, we prove that the time complexity of function *gain()* is O(*n*) firstly. Consider a candidate SCH *j'*. We try to improve the current solution by incorporating candidate SCH *j'* and possibly removing some candidate SCH *j* from *CSCHTemp*. The function gain() is the largest possible decrease in *TCSCHCost* + *TSRVCost* as a result. In line 3.1.1.2, we calculate *SRVCost_gain()* for each CH *i*. That is, we should check all CH *i*, as 1≤ *i*≤ n, which takes O(*n*) time. And In line 3.1.2, we calculate *CSCHCost_gain()* for each marked candidate SCH *j*, as the number of candidate SCH is at most m, which takes O(*m*) time. Because m is much less than n, the function *gain()* takes O(*n*).

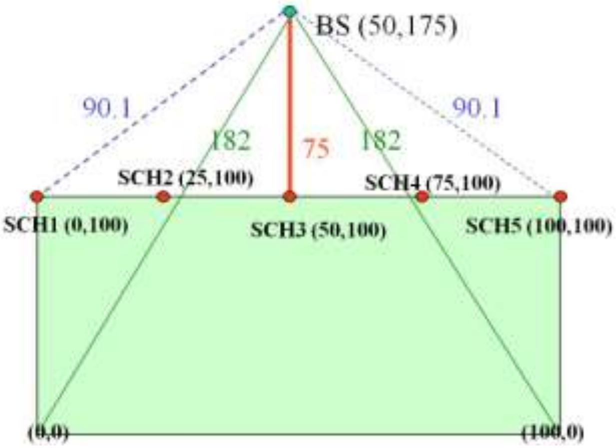

Fig. 3. Illustrative map of a WSN.

The outer loop of the improvement solution step is O(m), because 1≤ j'≤ m. Therefore, the improvement solution step take O($m*n$) time.

The initial solution step takes O($m*n$) time, and the improvement solution step takes O($m*n$) time. The time complexity of the SCH Configuration Algorithm is O($m*n$).

Lemma 2: *Each CH connects to exactly one candidate SCH.*

Proof. In the initial solution step, we sort the facility cost of all candidate SCHs firstly. Let the candidate SCH j_1 have minimum facility cost. All CHs will connect to the candidate SCH j_1, and then we add one candidate SCH in each turn incrementally. For each CH, if the total cost is less than currents' as introducing a new candidate SCH, we change the connection from the current candidate SCH to the new one. Thus, each CH connects to exactly one candidate SCH**.** In the improvement solution step, we examine each CH for each unconnected candidate SCH, if the *gain()*>0 resulting from incorporating a new candidate SCH, we change the connection from the current candidate SCH to the new one. That is, each CH connects to exactly one candidate SCH in our algorithm.

As shown in *Lemma 1*, the time complexity of the SCH configuration algorithm is given by O($m*n$), where m is the number of candidate SCHs and n is the number of CHs. The three-layer hierarchy scheme proposed in this study requires no more than a handful of SCHs to connect the CHs to the BS, and as a result, m is small. Furthermore, the number of CHs is equal to the number of clusters within the WSN, and thus n is also relatively small. As a consequence, the SCH configuration procedure has a low overall time complexity.

5 Energy Analysis

In this section, the energy cost of the proposed three-layer hierarchy is calculated using a simple energy model and is then compared with that of a conventional two-layer hierarchical network.

5.1 First-Order Radio Model

The first-order wireless transmission model in LEACH-C is applied in this model to the current three-layer hierarchy, the same parameter values as those applied in the LEACH-C are used to enable a like-for-like comparison to be made between the two schemes. According to this model, the energy consumed in the wireless transmission process is given by Equation (2) and (3).

$$E_{Tx}(l,d) = \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2, & \mathrm{d} < \mathrm{d}_0 \\ lE_{elec} + l\varepsilon_{mp}d^4, & \mathrm{d} \geq \mathrm{d}_0 \end{cases} \qquad (2)$$

$E_{Tx}(l,d)$ is the required energy for transmission, $\boldsymbol{l}$ is data length (bit) and $\boldsymbol{d}$ is distance.

Inside of distance $\boldsymbol{d_0}$, a free space model is used, and $\boldsymbol{\varepsilon_{fs}}$ is the amplifier energy factor in a free space model. Beyond $\boldsymbol{d_0}$, a multipath interference propagation model is used, and $\boldsymbol{\varepsilon_{mp}}$ is the amplifier energy factor in this model. When receiving a wireless signal, the estimated energy is:

$$E_{Rx}(l) = lE_{elec} \qquad (3)$$

$E_{Rx}(l)$ is the required energy for receiving, l is data length and E_{elec} is the consumed energy for per bit. This factor changes in different environments such as a wireless circuit or in data coding. In this model we assume that E_{elec} = 50 nJ/bit, ε_{fs} =10 $pJ/bit/m^2$, ε_{mp} =0.0013 $pJ/bit/m^2$. Then d_0 =87.7 m can be derived from Equations (2) and (3).

$$E_{Tx}(l,d_0)_{fs} = E_{Tx}(l,d_0)_{mp}$$
$$\Rightarrow lE_{elec} + l\varepsilon_{fs}{d_0}^2 = lE_{elec} + l\varepsilon_{mp}{d_0}^4$$
$$\Rightarrow \varepsilon_{fs}{d_0}^2 = \varepsilon_{mp}{d_0}^4$$
$$\Rightarrow d_0 = \sqrt{\varepsilon_{fs} / \varepsilon_{mp}} \cong 87.7 \ldots\ldots\ldots(4)$$

5.2 Energy Evaluation

Fig. 3 presents the simulation environment of LEACH-C [6] in which the sensor field is represented by the shaded area. As shown, the SCHs are distributed uniformly along the periphery of the sensor field. Note that this represents the worst-case SCH deployment scenario since the distance between the SCHs and the CHs is inevitably increased compared to the case in which the SCHs are deployed in the sensor field. Nonetheless, the three-layer cluster scheme still achieves better energy efficiency than the two-layer hierarchy.

The distance between the various points in the sensor field and the BS can be computed using basic geometric principles. The red bold line indicates the shortest distance between the sensed area and the BS and has a value of 75 m. Meanwhile, the green lines from (0,0) or (100,0), respectively, to the BS represent the distance(s) between the BS and the most remove point(s) and are found to have a length of 182 m. Finally, the maximum distance between the SCHs and the BS is indicated by the blue dotted line and has a value of 90.1 m.

By analyzing the map shown in Fig. 3, it is found that most transmission distances exceed d_0 (87.7m). If each sensor communicates directly with the BS, many transmissions adopt multipath interference propagation energy model in Equation (2). The outdoor range of the MICA2 is only 500 feet (about 152.4 m). Consequently, the CHs in a two-layer hierarchy will consume a significant amount of energy, and may even be unable to transmit directly to the BS in a real environment.

In LEACH-C, the CHs perform perfect data aggregation. Similarly, the SCHs perform data compression. The detailed definitions are shown later. To evaluate the energy efficiency of the cluster hierarchy scheme illustrated in the system flowchart in Fig. 2, we compute the upper bound of the energy consumption of three-layer cluster hierarchy and compare it with that of a two-layer hierarchy. *Theorem 1* and *Theorem 2* are the results of our analytic evaluation. For simplicity, energy consumption of the BS is ignored, and average cases are used in the following derivations.

Definition 5: Perfect Data Aggregation in a CH[6]
No matter how many individual data received from all sensors in a cluster, the CH can aggregate them into one single representative data.

Definition 6: Data Compression in an SCH
No matter how many individual data received from all connected CHs, the corresponding SCH can compress them into one single data with size smaller than $h*l$. where h is the number of CHs connected to the SCH and l represents the size of data.

Theorem 1: *The total energy consumption of the first-layer sensors in the proposed scheme is less than that in two-layer cluster hierarchy.*

Theorem 2: *The total energy consumption of the second-layer CHs in the proposed scheme is less than that in two-layer cluster hierarchy*.

For detailed proofs of *Theorem 1* and *Theorem 2,* please refer to the Appendix.

The overall lifetime of a WSN is limited by the energy resources of the sensors. That is, the addition of a large number of SCHs has no effect on the overall lifetime. Significantly, from *Theorem 1* and *Theorem 2,* it is apparent that the proposed three-layer cluster scheme yields an effective reduction in the energy consumption of the sensors (CHs are included) and therefore prolongs the lifetime.

6 Simulation

The performance of the proposed scheme was evaluated by performing a series of simulations. When performing the simulations, the Clustering and CH Selection module in the proposed scheme was implemented using the LEACH-C algorithm in order to compare the performance of the proposed hierarchy with that of a typical two-layer hierarchy. Thus, most parameters are set to be the same as those used in LEACH-C for fair comparison. The simulations solve the SCH configuration problem using the UFLP algorithm with a greedy local search method [16]. As indicated in Fig. 2, the proposed scheme has a modular-type structure, and thus while the current solution procedure uses the simulated annealing method and the UFLP algorithm to solve the CH and SCH configuration problems, respectively, these algorithms can be replaced by alternative methods if deemed appropriate.

In the simulations, the performance of the proposed scheme was evaluated in terms of the following metrics: the number of surviving nodes over time, the average energy dissipation over time, and the average network survival time as a function of the network area. In every case, the simulation results were obtained by averaging the results obtained in 10 consecutive runs performed under identical conditions. The energy dissipation model was based on that used in the LEACH-C and was assigned the same parameters, and the initial series of simulations considered a square sensor field as discussed in Section 5. The sensor field contained a total of 100 randomly distributed nodes, each of which had an initial energy of 2 J and transmitted data packet with a length of 500 bytes long. The message packet was assumed to have a length of 25 bytes. Transmission range of a sensor is 100 m. The energy consumed by each CH in performing the

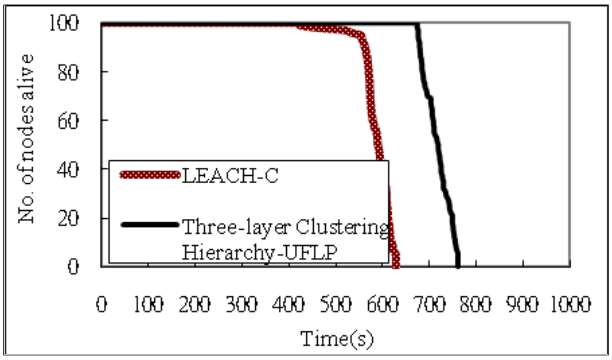

Fig. 4. Variation of surviving nodes.

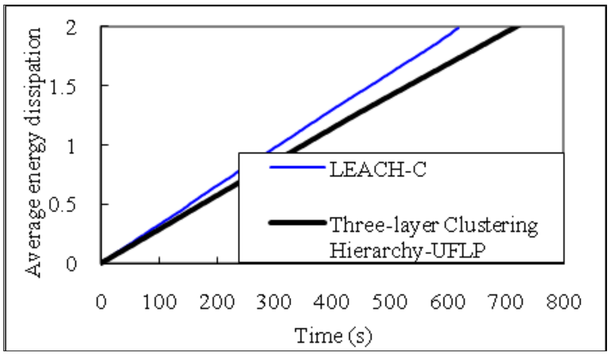

Fig. 5. Variation of average energy dissipation.

data aggregation process was specified as E_{DA}=5 *nJ/bit/signal*, while that consumed by the SCHs in compressing the data prior to its transmission to the BS was defined as E_{DP}, which is assumed to be the same as E_{DA}. Thus E_{DP}=5 *nJ/bit/signal*.

In the simulations, the SCHs were all assumed to have the same initial energy capacity, which was specifically assigned a value greater than that of the CHs and sensors. However, in deploying the network, the aim is to minimize the cost as far as possible. In practice, this tradeoff is determined by the energy capacity of the SCHs. For example, in the event that the SCHs have only a limited energy capacity, the number of SCHs should equal the number of CHs in order to achieve a balanced load within the SCH layer. By contrast, if the SCHs have high-energy capacity, or transmit via broadband over a power line, the number of SCHs could be small.

In a cluster hierarchy, the number of nodes in one layer should be less than or equal to the number of nodes in the layer below it. Therefore, in the proposed hierarchy, the number of SCHs should not exceed the number of CHs. The experimental results presented by Heinzelman et al. [6] showed that five clusters were sufficient for the conditions considered in the present simulations. Thus, the number of SCHs was specified as five. These SCHs were uniformly distributed throughout the simulated sensor field in such a way that they were closer to the BS than any of the CHs or sensors. As described earlier, following their deployment, some of these SCHs were activated by the SCH configuration algorithm, while the remainders were put to sleep to conserve their energy resources.

Since the sensors in the first layer of the network have an initial energy of 2 J, the SCHs in the third layer were assumed to have an initial energy of 6 J. Note that through a series of simulation (results not shown here), it was shown that even if the SCHs were assigned an initial energy greater than 6 J, no net improvement in the overall energy efficiency of the WSN was achieved since the energy efficiency is constrained by the initial energy capacity of the lowest-level nodes.

Finally, the time-out parameter used in the steady state phase to trigger a new re-clustering / reconfiguration procedure was specified as 1 second.

In the first simulation, the results of the simulated annealing algorithm confirmed that a total of five CHs were required to support the sensors. Executing the UFLP scheme, it was found that two active SCHs were required in the SCH layer. Thus, in each operational round of the proposed scheme, two SCHs were activated, while the remaining three SCHs were put to sleep.

Fig. 4 illustrates the variation in the number of surviving nodes in the two-layer and three-layer hierarchies over time. It can be seen that the final sensor fails after around 760 seconds in the proposed hierarchy, but fails after just 620 seconds in LEACH-C. The proposed hierarchy yields a significant improvement in the lifetime. In addition, it can be seen that in LEACH-C, the first node becomes inactive after around 420 seconds, while the final node dies some 200 seconds later. By contrast, in the proposed scheme, the first node dies after 700 seconds and is followed by the final node just 20 seconds later. In other words, the proposed scheme yields a significant improvement in the load balance within the network compared to that obtained using the LEACH-C clustering method.

When all of the sensors in the lowest level of the proposed hierarchy have died, the five SCHs in the upper-most layer of the architecture still possess a certain amount of residual energy. That is, the energy cost expended in improving the lifetime of LEACH-C by an additional 140 seconds is less than 5*6 J. It is worth stressing here that the improvement in the lifetime is not the result of the provision of additional energy in the SCH layer, but the flexibility which this layer gives in balancing the load throughout the WSN. The results clearly show that through a minimal expenditure on a small

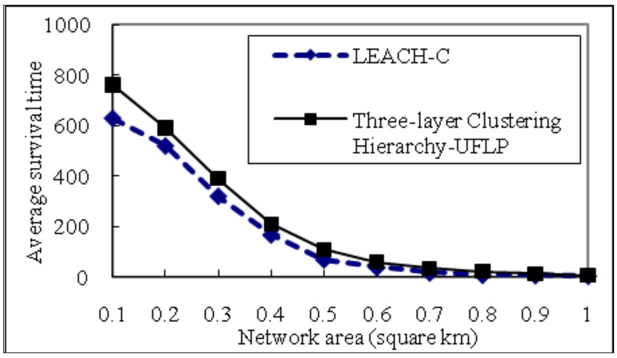

Fig. 6. Variation of average network survival time as function of network area.

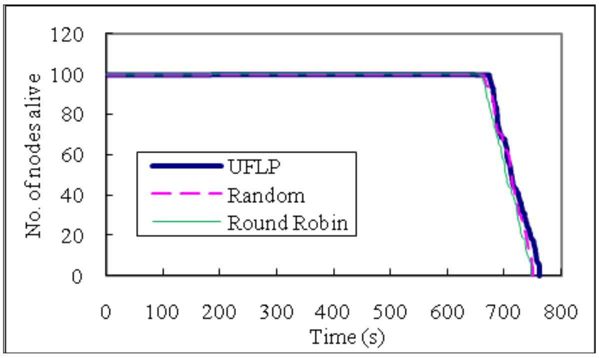

Fig. 7. Variation of surviving nodes over time with SCH layer configured using three different methods.

number of SCH devices, a significant improvement can be obtained in the lifetime.

Fig. 5 illustrates the variation of the average energy dissipation over time in the two-layer and three-layer networks. It can be seen that in the proposed hierarchy, the average energy dissipation reaches 2 J after 730 seconds rather than at the lifetime of 760 seconds. This discrepancy is to be expected since the initial total average energy of the 105 sensors in the proposed hierarchy (i.e. 5 SCHs and 100 CHs/sensors) is slightly higher than 2 J (i.e. 230/105=2.19 J). From inspection, it can be seen that in LEACH-C, the average dissipated energy reaches a value of 2 J after around 620 seconds. Thus, the results confirm that the improved load balance achieved in the proposed hierarchy configured using the UFLP/LEACH-C algorithms results in a lower energy dissipation rate than that in a two-layer structure configured using LEACH-C only.

In a second series of experiments, the number of CH/sensors and SCHs remained unchanged (i.e. 100 and 5, respectively), but the size of the sensor field was varied over the range 0.1~1.0 Km^2. Clearly, as the size of the sensor field increases, the distance over which the sensors are required to transmit also increases. As a result, the rate at which these sensors consume their energy resources also increases, and thus the average survival time of the nodes reduces. Fig. 6 shows that the average survival times of the proposed hierarchy deployed in sensor fields of size 0.1, 0.5 and 1.0 Km^2 are 760, 110 and 7 seconds, respectively. By contrast, the corresponding survival times of LEACH-C are 620, 71 and 6 seconds, respectively. Thus, it is apparent that the proposed scheme retains its advantage over LEACH-C as the size of the sensed area increases.

A final series of simulations was performed to compare the effect of the method used to configure the SCH layer of the proposed hierarchy on the survival time of the network. The simulations considered three different configuration schemes, namely the UFLP scheme, a random scheme, and a round-robin scheme. In the random scheme, each CH was simply connected to a randomly chosen SCH, while in the round-robin scheme, all of the CHs were connected to a single SCH in turn.

Fig. 7 illustrates the variation of the number of surviving nodes within networks deployed in a sensor field of size 0.1 Km^2 and configured using each of the three different methods. From inspection, it is determined that the first sensors die after 672, 663 and 658 seconds in the UFLP, random and round-robin networks, respectively, while the final sensors die after 761, 750 and 746 seconds. Thus, the results show that the UFLP scheme yields a small improvement in the lifetime when the sensor field has a relatively small size.

Fig. 8 presents the equivalent results for the case where the size of the sensor field is increased from 0.1 Km^2 to 0.4 Km^2. In this case, the lifetimes of the UFLP, random and round-robin networks are found to be 318, 174 and 197 seconds, respectively. In other words, even though the lifetime reduces significantly as the size of the sensor field increasing, the lifetime improvement obtained by the UFLP scheme is considerably greater than that obtained using either the random or the round-robin schemes. The efficacy of the UFLP configuration scheme improves relative to that of the other two schemes as the size of the sensor field increases. The reduction in the lifetime with an increasing sensing area is to be expected since for a given number of deployed nodes, the transmission distances of the CHs and sensors increase as the size of the sensor field increases. Nonetheless, the results confirm that the policy of the UFLP scheme in considering both the remaining energy of the SCHs and CHs and the transmission distance when configuring the SCH layer results in an improved load balance and therefore yields a considerable improvement in the lifetime.

Finally, Fig. 9 illustrates the variation of the average survival time with the network area for

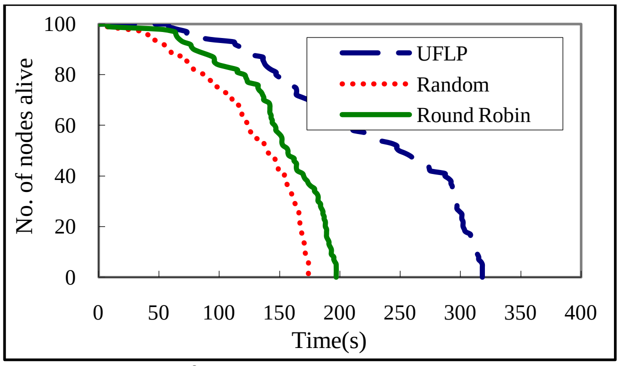

Fig. 8. Variation of surviving nodes over time with SCH layer configured using three different methods.

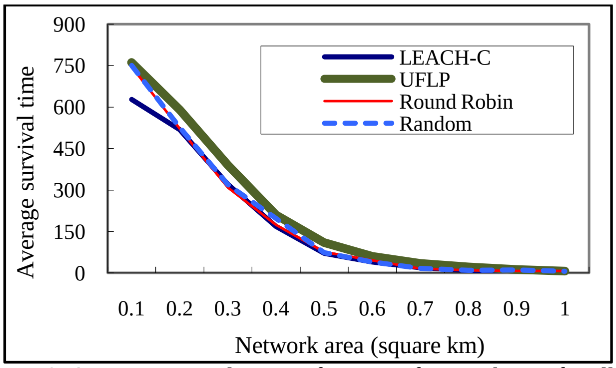

Fig. 9. Average survival time as function of network area for all methods.

LEACH-C and three-layer hierarchies in which the SCH layers are configured using the UFLP, random or round-robin schemes, respectively. The results confirm that the UFLP clustering scheme consistently outperforms the other three schemes irrespective of the network size. As discussed above, this performance improvement is the result primarily of the facility and service cost functions used in the SCH configuration procedure, which specifically consider the impact of the transmission distance on the remaining energy resources of a node when considering which SCH nodes to activate and how best to connect these nodes to the CHs in the second layer of the architecture.

Compared to conventional two-layer clustering schemes such as LEACH-C, the proposed hierarchy method proposed in this study incurs a slightly higher cost due to the requirement for a small number of SCHs and the need to physically deploy these SCH devices within (or near) the sensing area and then configure/schedule the SCH layer. However, the simulation results presented in Figs. 4~9 indicate that these additional costs yield a significant improvement in the network performance.

7 Conclusions

This study has proposed a three-layer cluster hierarchy scheme with a modular structure for the energy efficiency of WSNs. The network topology is dynamically reconfigured to take account of changes in the energy resources of the nodes and the physical positions of the CHs and sensors. In the proposed scheme, the appropriate number of clusters within the sensor field and the choice of CHs within these clusters are determined by the BS using a simulated annealing algorithm. Meanwhile, the energy-efficient configuration of the SCH layer positioned between the BS and the CH layer is determined using an uncapacitated facility location algorithm. The proposed scheme avoids the need to specify the number of CHs and active SCHs in advance and has the ability to reconfigure the network topology on a dynamic basis in order to respond to changes in the states and locations of the various nodes within the network. Furthermore, any nodes which are not currently scheduled for transmission are put to sleep to conserve their energy resources. A major advantage of the three-layer cluster hierarchy scheme compared to two-layer scheme is its suitability for deployment in hostile or otherwise impenetrable environments such as battlefields, jungles, and so forth.

The performance of the three-layer cluster hierarchy scheme has been evaluated by performing a series of simulations. The results have shown that the scheme outperforms LEACH-C in terms of the number of surviving nodes over time, the average energy dissipation over time, and the average survival time of the nodes as a function of the network area. In other words, the results confirm that the addition of the third layer of enhanced-capability nodes and the dynamic configuration of this layer using the uncapacitated facility location algorithm result in an improved load balance throughout the WSN network, and extend its lifetime as a result.

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APPENDIX

For brevity of discussions, the following notations are defined and followed by the derivations of energy consumptions for different architectures.

Notations:

- n: the number of sensors.
- c: the number of clusters. (i.e. the number of CHs.)
- $\overline{n_c}$: the average number of sensors in each cluster.
- m: the number of SCHs.
- k: the number of active SCHs.
- $\bar{h}$: the average number of CHs connected to an active SCH.
- $\overline{d_{s,CH}}$: the average distance from a sensor to its CH.
- $\overline{d_{s,SCH}}$: the average distance from a sensor to an SCH.
- $\bar{s}$: the average number of sensors, which each SCH direct receives information from before the topology built.
- $\overline{d_{CH,SCH}}$: the average distance from a CH to its connected active SCH.
- $\overline{d_{SCH,BS}}$: the average distance from an active SCH to the BS.
- $\overline{d_{CH,BS}}$: the average distance from a CH to the BS.
- $\overline{d_{s,BS}}$: the average distance from a sensor to the BS.
- l: the size of data packet (bits).
- $\bar{l}$: the average size of compressed data packet (bits).
- t: the size of message packet (bits).
- $\bar{t}$: the average size of compressed message packet (bits).
- E_{DA}: the energy for perfect data aggregation.
- E_{DP}: the energy for data compression.
- E_s: the energy for scheduling.

Lemma 3: *The total energy consumption of the first-layer sensors in the proposed scheme is* $nE_{Tx}(t,\overline{d_{s,SCH}})+(n-c)E_{Rx}(t)+(n-c)E_{Tx}(l,\overline{d_{s,CH}})$.

Proof. We show the total energy consumption of the first-layer sensors in the setup phase is $nE_{Tx}(t,\overline{d_{s,SCH}})+(n-c)E_{Rx}(t)$ firstly and then is $(n-c)E_{Tx}(l,\overline{d_{s,CH}})$ in the steady state phase. In the setup phase, the total energy consumption of a sensor includes (1) broadcasting its energy level and position to SCHs in its transmission range, which consumes $E_{Tx}(t,\overline{d_{s,SCH}})$, and (2) receiving the topology result and the sensor layer schedule from its CH, which consumes $E_{Rx}(t)$. So, the total energy dissipation of the first-layer sensors is $nE_{Tx}(t,\overline{d_{s,SCH}})+(n-c)E_{Rx}(t)$ (the CHs excluded from sensors after clusters and CHs being found). In the steady state phase, a sensor sends data to its CH in its transmission turn, which consumes $E_{Tx}(l,\overline{d_{s,CH}})$. Thus, the total energy consumption of the first-layer sensors is $(n-c)E_{Tx}(l,\overline{d_{s,CH}})$ .Therefore, the total energy consumption of the first-layer sensors in the proposed scheme is $nE_{Tx}(t,\overline{d_{s,SCH}})+(n-c)E_{Rx}(t)+(n-c)E_{Tx}(l,\overline{d_{s,CH}})$.

Lemma 4: *The total energy consumption of the second-layer CHs in the proposed scheme is* $c(E_{Rx}(t)+E_s+\overline{n_c}E_{Tx}(t,\overline{d_{s,CH}}))+c(\overline{n_c}E_{Rx}(l)+E_{DA}+E_{Tx}(l,\overline{d_{CH,SCH}}))$.

Proof. We show the total energy consumption of the second-layer CHs in the setup phase is $c(E_{Rx}(t)+E_s+\overline{n_c}E_{Tx}(t,\overline{d_{s,CH}}))$ firstly and then is $c(\overline{n_c}E_{Rx}(l)+E_{DA}+E_{Tx}(l,\overline{d_{CH,SCH}}))$ in the steady state phase. In the setup phase, the total energy consumption of a CH includes (1) receiving the topology result and the second-layer schedule from its connected SCH, which consumes $E_{Rx}(t)$, (2) scheduling the first-layer, which consumes E_s and (3) sending the topology result and schedule to its cluster member sensors, which consumes $\overline{n_c}E_{Tx}(t,\overline{d_{s,CH}})$. So, the total energy dissipation of the second-layer CHs is $c(E_{Rx}(t)+E_s+\overline{n_c}E_{Tx}(t,\overline{d_{s,CH}}))$. In the steady state phase, the total energy consumption of a CH includes (1) receiving data from sensors in its cluster by the first-layer schedule, which consumes $\overline{n_c}E_{Rx}(l)$, (2) aggregating data, which consumes E_{DA} and (3) sending data to its corresponding active SCH in its transmission turn, which consume $E_{Tx}(l,\overline{d_{CH,SCH}})$. Thus, the total energy consumption of the second-layer CHs is $c(\overline{n_c}E_{Rx}(l)+E_{DA}+E_{Tx}(l,\overline{d_{CH,SCH}}))$. Therefore, the total energy consumption of the second-layer CHs in our approach is $c(E_{Rx}(t)+E_s+\overline{n_c}E_{Tx}(t,\overline{d_{s,CH}}))+c(\overline{n_c}E_{Rx}(l)+E_{DA}+E_{Tx}(l,\overline{d_{CH,SCH}}))$.

Lemma 5: *The total energy consumption of the third-layer SCHs in the proposed scheme is* $m(\bar{s}E_{Rx}(t)+E_{DP}+E_{Tx}(\bar{t},\overline{d_{SCH,BS}}))+mE_{Rx}(t)+k(E_s+\bar{h}E_{Tx}(t,\overline{d_{CH,SCH}}))+k(\bar{h}E_{Rx}(l)+E_{DP}+E_{Tx}(\bar{l},\overline{d_{SCH,BS}}))$.

Proof. We show the total energy consumption of the third-layer SCHs in the setup phase is $m(\bar{s}E_{Rx}(t)+E_{DP}+E_{Tx}(\bar{t},\overline{d_{SCH,BS}}))+mE_{Rx}(t)+k(E_s+\bar{h}E_{Tx}(t,\overline{d_{CH,SCH}}))$ firstly and then is $k(\bar{h}E_{Rx}(l)+E_{DP}+E_{Tx}(\bar{l},\overline{d_{SCH,BS}}))$ in the steady state phase. In the setup phase, the total energy consumption of an SCH includes (1) receiving information from sensors, compressing received message, and sending compressed message to the BS, which consumes $\bar{s}E_{Rx}(t)+E_{DP}+E_{Tx}(\bar{t},\overline{d_{SCH,BS}})$, (2) receiving the topology result and the third-layer schedule from the BS, which consumes $E_{Rx}(t)$ and (3) an active SCH scheduling the second-layer, and sending the topology result and the schedule to all corresponding CHs, which consumes $E_s+\bar{h}E_{Tx}(t,\overline{d_{CH,SCH}})$. So, the total energy dissipation of the third-layer SCHs is

$m(\bar{s}E_{Rx}(t)+E_{DP}+E_{Tx}(\bar{t},\overline{d_{SCH,BS}}))+mE_{Rx}(t)+k(E_s+\bar{h}E_{Tx}(t,\overline{d_{CH,SCH}}))$.
In the steady state phase, the total energy consumption of an active SCH includes (1) receiving data from connected CHs by the second-layer schedule, which consumes $\bar{h}E_{Rx}(l)$, (2) compressing data, which consumes E_{DP} and (3) sending data to the BS in its transmission turn, which consumes $E_{Tx}(\bar{l},\overline{d_{SCH,BS}})$. Thus, the total energy consumption of active SCHs is $k(\bar{h}E_{Rx}(l)+E_{DP}+E_{Tx}(\bar{l},\overline{d_{SCH,BS}}))$. Therefore, the total energy consumption of the third-layer SCHs in the proposed scheme is $m(\bar{s}E_{Rx}(t)+E_{DP}+E_{Tx}(\bar{t},\overline{d_{SCH,BS}}))+mE_{Rx}(t)+k(E_s+\bar{h}E_{Tx}(t,\overline{d_{CH,SCH}}))+k(\bar{h}E_{Rx}(l)+E_{DP}+E_{Tx}(\bar{l},\overline{d_{SCH,BS}}))$.

Correspondingly, we calculate total energy consumption of two-layer cluster hierarchy as follows.

Lemma 6: *The total energy consumption of the first-layer sensors in two-layer cluster hierarchy is* $nE_{Tx}(t,\overline{d_{s,BS}})+(n-c)E_{Rx}(t)+(n-c)E_{Tx}(l,\overline{d_{s,CH}})$.

Proof. We show the total energy consumption of the first-layer sensors in the setup phase is $nE_{Tx}(t,\overline{d_{s,BS}})+(n-c)E_{Rx}(t)$ firstly and then is $(n-c)E_{Tx}(l,\overline{d_{s,CH}})$ in the steady state phase. In the setup phase, the total energy consumption of a sensor includes (1) broadcasting its energy level and position to the BS, which consumes $E_{Tx}(t,\overline{d_{s,BS}})$ and (2) receiving the topology result and the first-layer schedule from its CH, which consumes $E_{Rx}(t)$. So, the total energy dissipation of the first-layer sensors is $nE_{Tx}(t,\overline{d_{s,BS}})+(n-c)E_{Rx}(t)$ (the CHs excluded from sensors after clusters and CHs being found). In the steady state phase, the total energy consumption of the first-layer sensors is $(n-c)E_{Tx}(l,\overline{d_{s,CH}})$. This is the same as that of the proposed scheme (see the proof in *Lemma 3*). Therefore, the total energy consumption of the first-layer sensors in two-layer cluster hierarchy is $nE_{Tx}(t,\overline{d_{s,BS}})+(n-c)E_{Rx}(t)+(n-c)E_{Tx}(l,\overline{d_{s,CH}})$.

Lemma 7: *The total energy consumption of the second-layer CHs in two-layer cluster hierarchy is* $c(E_{Rx}(t)+E_s+\overline{n_c}E_{Tx}(t,\overline{d_{s,CH}}))+c(\overline{n_c}E_{Rx}(l)+E_{DA}+E_{Tx}(l,\overline{d_{CH,BS}}))$.

Proof. We show the total energy consumption of the second-layer CHs in the setup phase is $c(E_{Rx}(t)+E_s+\overline{n_c}E_{Tx}(t,\overline{d_{s,CH}}))$ firstly and then is $c(\overline{n_c}E_{Rx}(l)+E_{DA}+E_{Tx}(l,\overline{d_{CH,BS}}))$ in the steady state phase. In the setup phase, the total energy consumption of the second-layer CHs is $c(E_{Rx}(t)+E_s+\overline{n_c}E_{Tx}(t,\overline{d_{s,CH}}))$. This is the same as that of the proposed scheme (see the proof in *Lemma 4*). In the steady state phase, the total energy consumption of a CH includes (1) receiving data from sensors in its cluster by the sensor layer schedule, which consumes $\overline{n_c}E_{Rx}(l)$, (2) aggregating data, which consumes E_{DA} and (3) sending data to the BS in its transmission turn, which consumes $E_{Tx}(l,\overline{d_{CH,BS}})$. So, the total energy dissipation of the second-layer CHs is $c(\overline{n_c}E_{Rx}(l)+E_{DA}+E_{Tx}(l,\overline{d_{CH,BS}}))$. Therefore, the total energy consumption of the second-layer CHs in two-layer cluster hierarchy is $c(E_{Rx}(t)+E_s+\overline{n_c}E_{Tx}(t,\overline{d_{s,CH}}))+c(\overline{n_c}E_{Rx}(l)+E_{DA}+E_{Tx}(l,\overline{d_{CH,BS}}))$.

From the analyses in *Lemmas 3~7*, we see that there are two parts are the same in the proposed cluster scheme and two-layer cluster hierarchy. It can be seen that the total energy consumption of the CHs nominated in the setup phase of the current scheme, and the total energy consumption of the sensors in the steady state phase, are equal to the equivalent total energy consumptions in the two-layer hierarchy. This result is to be expected since the lower two layers in the proposed cluster scheme are the same as two-layer cluster hierarchy, and the sensors are assumed to have equivalent capabilities in the two cases to enable a fair comparison to be made between the two methods. The comparisons of total energy consumption of sensors and CHs are given in *Theorem 1* and *Theorem 2*.

Theorem 1: *The total energy consumption of the first-layer sensors in the proposed scheme is less than that in two-layer cluster hierarchy.*

Proof. From *Lemma 3* and *Lemma 6*, the difference in the total energy consumption of the first-layer sensors between the proposed cluster hierarchy and two-layer cluster hierarch is the part of $nE_{Tx}(t,\overline{d_{s,SCH}})$ and $nE_{Tx}(t,\overline{d_{s,BS}})$. If both methods use the same energy model, as $\overline{d_{s,BS}}$ is larger than $\overline{d_{s,SCH}}$, the proposed cluster scheme is more energy efficient than two-layer cluster hierarchy. Besides, $\overline{d_{s,SCH}}$ is usually less than 87.7 m, the free space model will be adopted and $E_{Tx}(t,\overline{d_{s,SCH}})$ will be assigned by $tE_{elec}+t\varepsilon_{fs}\overline{d_{s,SCH}}^2$ in the proposed scheme. Contrarily, $\overline{d_{s,BS}}$ is frequently larger than 87.7 m, the multipath fading model will be adopted and $E_{Tx}(t,\overline{d_{s,BS}})$ will be assigned by $tE_{elec}+t\varepsilon_{mp}\overline{d_{s,BS}}^4$ in two-layer cluster hierarchy. The difference in these two methods greatens. Therefore, the total energy consumption of the first-layer sensors in the proposed scheme is less than that in two-layer cluster hierarchy.

Theorem 2: *The total energy consumption of the second-layer CHs in the proposed scheme is less than that in two-layer cluster hierarchy.*

Proof. From *Lemma 4* and *Lemma 7*, the difference in the total energy consumption of the second-layer CHs between the proposed cluster hierarchy and two-layer cluster hierarch is the part of $cE_{Tx}(l,\overline{d_{CH,SCH}})$ and $cE_{Tx}(l,\overline{d_{CH,BS}})$. If both methods use the same energy model, as $\overline{d_{CH,BS}}$ is larger than $\overline{d_{CH,SCH}}$, the proposed cluster scheme is more energy efficient than two-layer hierarchy. Besides, $\overline{d_{CH,SCH}}$ is usually less than 87.7 m, the free space model will be adopted and $E_{Tx}(l,\overline{d_{CH,SCH}})$ will be assigned by

$lE_{elec} + l\varepsilon_{fs}\overline{d_{CH,SCH}}^2$. Contrarily, $\overline{d_{CH,BS}}$ is frequently larger than 87.7 m, the multipath fading model will be adopted and $E_{Tx}\left(l, \overline{d_{CH,BS}}\right)$ be assigned by $lE_{elec} + l\varepsilon_{mp}\overline{d_{CH,BS}}^4$. The difference in these two methods greatens. Therefore, the total energy consumption of the second-layer CHs in the proposed cluster scheme is less than two-layer cluster hierarchy.

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