An Energy-Efficient Cluster-Head Selection Protocol for Energy-Constrained Wireless Sensor Networks

Peng Hao, Wanzhi Qiu, and Rob Evans

National ICT Australia
Department of Electrical and Electronic Engineering, The University of Melbourne
Parkville, Victoria 3010, Australia
{peng.hao,wanzhi.qiu,rob.evans}@nicta.com.au

Abstract. In clustered wireless sensor networks, cluster-heads (CHs) are the key. And the CH selection methods can affect the efficiency of the cluster and even influence the lifetime of an energy-constrained network. In this paper, we propose the Energy-consumption-cycle based Cluster-heads Selection (ECHS) protocol. ECHS selects CHs via two phases. In the first phase, CH candidates are chosen based on an adaptable energy threshold and the status of neighbor nodes. In the second phase, each candidate computes its own Energy Consumption Cycles (*ECC*), which is relevant to the CH candidate's residual energy and the energy consumption when communicating with its neighbor nodes. The *ECC* actually evaluates the lifetime of the potential cluster. Hence the CH candidate with both higher residual energy and higher *ECC* has more possibility to be the CH. By comparing *ECC*, the suitable CHs can be obtained. Simulation results illustrate that ECHS protocol prolongs the network lifetime and also increases the amount of data received at BS.

Keywords: Energy-constrained WSNs, cluster-head selection protocol, energy consumption cycle, lifetime.

1 Introduction

Wireless sensor networks (WSNs) have been catering both academic research and industrial applications for several decades, motivated by the advancement in micro-electro-mechanical systems (MEMS) and ever-increasing demands from the real world. Especially since the end of the last century, it's been one of the hottest research spots. Nowadays, these state-of-art WSNs have been penetrating into almost every aspects of the human life, such as target tracking, surveillance, environment monitoring, and home automation etc. Particularly in battlefields, volcanoes, and other hostile or hash environment, WSNs play an irreplaceable role. Lots of research literatures and practical systems have been contributing to the improvement, in terms of data-rate, channel assignment, and device size, etc. Though widely applied, there are still at least two bottlenecks, namely, the data rate and the energy issue [1]. The former is comparatively less intractable, since there are various wireless communication protocols with different data rates from about 20kbps (IEEE 802.

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15.4) [18] to over 2Gbps (IEEE 802.15.3c) [19], people can adopt the suitable one according to the application background. However, the energy consumption issue becomes more crucial, especially in the case that the batteries are neither rechargeable nor replaceable. Hence, WSNs are expected to be designed properly such that the network can work in an energy-efficient way.

In general, the energy is consumed in three ways, data sensing, computing and communication. These first two consumption aspects normally can be neglected [15], while the last one costs the most. According to [1], the energy cost of transmitting *l*-bit data within a distance of *d* can be modeled by (1).

$$E_{Tx}\left(l,d\right)=lE_{elec}+l\varepsilon d^{\alpha}=\begin{cases} lE_{elec}+l\varepsilon_{fs}d^{2}, d<d_{0} \\ lE_{elec}+l\varepsilon_{mp}d^{4}, d\geq d_{0}\end{cases} \tag{1}$$

And the energy consumed when receiving *l*-bit data is $E_{Rx}\left(l\right)=lE_{elec}$. Herein d_0 is called the crossover distance and presented by $d_0=\sqrt{\varepsilon_{fs}/\varepsilon_{mp}}$ [20]. ε_{fs} and ε_{mp} show the different value of transmit amplifier with regard to the distance. Equation (1) tells that the distance d dominates the energy consumption, which becomes dramatic soar when the distance is larger than or equal to d_0. Hence, in this paper, we assume that the normal node's communication range should be less than d_0 such that its energy consumption can be reasonably restricted. That's to say, nodes generally work in the basic power level [3].

It turns out to be compromise between energy consumption and network functions. Gathered data and the maintenance message must be transmitted between the nodes and BS. BS can be far away from the WSN and energy-unconstrained, its communication range covers the whole deployment of the network. And CHs are the nodes to be responsible for the communication with BS. Since clustered WSN, we divide the nodes into CHs and cluster members (CMs), according to the working status. For the simplicity, we assume that only the CHs can dynamically change its transmission range such that it can both talk to the CMs (in a basic power level, $d<d_0$), and the BS (in higher levels, $d\geq d_0$).

We note that all the WSNs, even each node is initialized with the high enough energy, can always change into energy-constrained networks after a long enough period of time. Hence it's necessary to draw attention to the energy-constrained networks due to the extensive existence. This paper focuses on the CH searching protocol for these WSNs. The initial energy of these nodes is randomly generated with a certain energy ranges. Namely, the values of their residual energy vary among the network, due to the energy-constrained condition. The proposed protocol in this paper is to build an energy-efficient network, in which the mission of the WSN is to send the sensed data to BS. Herein we propose a two-phase strategy in order to determine the CHs. The first phase is responsible for identifying CHs candidates, using an adaptive energy threshold. In the second phase, we introduce the energy consumption cycles (*ECC*) to determine the CHs among these CH candidates. The energy consumption cycles represents the ratio of residual energy of the CH candidate and its energy expenditure when communicating with neighbor nodes. The more cycles, the longer that the cluster can work. That's to say, the value of *ECC* actually evaluates the longevity of the cluster and also implies the lifetime of the network. By computing and comparing the *ECC* of CHs candidates, CHs are finally determined and clusters are built up. This novel threshold represents the dynamic nature of nodes' residual energy and the relationship between the CH and CMs. Moreover, it enables the possibility to estimate the lifetime of the network.

The improper CH can impair the performance of the network, in terms of low efficiency, limited throughput and shortened lifetime. In our work, we look forward to the cluster which is built up by the relatively high residual-energy CH, with the fairly low intra-cluster communication energy cost. The parameter of *ECC* is proposed to choose such CHs. This kind of cluster can be regarded to extend the network lifetime, and accomplish the WSN functions efficiently.

The rest of this paper is arranged as follows. In Section 2, we briefly overview the related methods in CH selection and discuss the motivation of ECHS. In Section 3, we propose the ECHS in details by introducing the two-phase selection procedure. Simulations in Section 4 demonstrate the efficiency and reliability of this protocol, compared with the other two methods; and finally we conclude our work in Section 5.

2 Related Work

As for routing strategies, cluster-based structure has been recognized as an energy-efficient way to prolong the system lifetime [1]. Particularly in medium or large-sized WSNs, CHs gather the data from inner cluster nodes and transmit the compressed packages to BS. This scheme reduces the global overhead and prevents the unnecessary energy consumption [5], [6].

When organizing a WSN into clusters, CH selection is the vital step. Basically, there are at least three essential issues, i.e. (i) the number of the CHs or the size of the clusters; (ii) the criteria for CH selection; and (iii) intra-/inter-cluster communication scheme. These three issues should be concerned in the cluster-based WSN in order to form an energy-efficient and self-organized network.

Various CH selection schemes have been proposed in addressing these three issues. LEACH [1] is a well-known protocol which defines the optimal CH percentage, and randomly rotates CH to save energy. Many subsequent research is based on LEACH protocol, such as LEACH-C (LEACH-Centralized) [7] and LEACH-F (LEACH with Fixed clusters) [8]. These methods use BS as the centralized control. The LEACH related research shows that CHs rotating can distribute and balance the energy dissipation. Other than random rotation, weight/threshold based protocols are introduced to the CH selection. HEED [3] distinguishes the nodes into two types, powerful nodes serving as CHs and normal nodes working as CMs, and also proposes a so-called cluster radius to define the transmission power in intra-cluster communication broadcast. CHs are finally selected by the residual energy and the secondary parameter, such as node proximity to its neighbors or node degree. Similarly, DECP [13] also concerns the number of neighbor nodes, their remaining energy and the mutual distances.

Meanwhile like HEED, some research [2], [4] classifies nodes into these fixed two types above based on the residual energy. However, due to the unequal energy depletion, the powerful node actually turns out to be a normal one when its residual energy becomes comparatively small; while on the other hand, the normal nodes can serve as CHs as well. In summary, fixing the roles of nodes based on their initial energy does not reflect the dynamic nature of nodes energy status.

As illustrated in (1), since the distance is the dominant factor in energy consumption, many literatures address their research in location/distance issue. In [8], [9] and [10], nodes are equipped with GPS-capable devices, since nodes are assumed to be randomly deployed. However, GPS-capable devices not only increase the system complexity and the cost, but also burden the energy consumption. Furthermore, limited GPS accuracy actually cannot guarantee the precise enough location of these nodes in medium-sized WSNs, and even worse for the small-sized WSNs. Hence these devices may not be as reliable as expected and could even mislead the CH selection. In our work, these high-cost and energy-expensive GPS-capable devices are not involved. Actually, many literatures have ignored the fact that in practice, distance is not essential unless the one of the missions is to find out the location of nodes. The truth is this consumption can be calculated directly by the node itself. For example, the node can easily work out the energy loss after a certain length of data transmission or receiving. It's more reliable and precise than using (1). In our work, since the purpose is to gather the data from the outside world and a certain range has been predefined, we don't concern the location issue.

A WSN can be considered as an energy-constrained network, if the residual energy of each node in this network is (initially) limited and the transmission power level is (conditionally) restricted. This means the case that generally the nodes can only talk to the other nodes within a certain range. Herein, we concern the first condition because of the dynamic energy status of these nodes. As mentioned above, if the roles (powerful nodes and normal nodes) are not fixed, the nodes can then swap the roles when necessary according to the residual energy, such that the network is more flexible and the energy dissipation can be balanced. Meanwhile, we take into account the second condition due to the dramatic energy consumption. As illustrated in (1), when the distance between two nodes is larger than the crossover distance, the energy is consumed in the much higher exponential way. Hence, with the assumption of the limited transmission range (less than crossover distance), we keep the nodes working with the basic power level. In this paper, we also suppose that only CHs can raise the power level in order to talk to BS. Also, without loss of generality, as the work in [1], we assume the one-hop communication between CHs and BS, thus the time delay can be avoided, and moreover, interferences among either CHs or CHs and CMs do not need to be concerned.

For seeking the cluster with higher residual-energy CH and less intra-cluster communication cost, we need the weight/threshold to tailor the CH selection. Based on the discussing above, we put a residual energy constrain, which makes the first phase to keep the selection in the correct way. Meanwhile, we need to alter the threshold to present the dynamic relationship of these CHs and their CMs. These conditions result in the two-phase CH selection scheme, namely, the Energy-consumption-cycle based CH selection (ECHS) protocol.

3 ECHS Protocol

ECHS protocol contains two periods, shown in Fig. 1, namely, cluster set-up period based on two-phase CH selection method, and steady state period based on energy consumption cycle scheme. These two periods determine the lifetime of the cluster. We firstly make four assumptions for the energy-constrained WSNs. These assumptions below are also realistic in the real application.

- Both BS and nodes in WSNs are stationary. The self-maintained sensor nodes are transmission-range-limited and randomly deployed with enough connectivity [14]; each node has a pre-defined unique ID. The energy consumption of BS is unconcerned. The CHs density is subject to the work in LEACH [1].
- The power levels of these nodes are conditional. Only the nodes serving as CHs are capable to change the level for the communication with BS. And all the other nodes work in the basic power level with the limited transmission range, which is less than the crossover distance of d_0. In particular, CHs can reduce the power level to the basic one again when returning its role as normal nodes.
- The nodes have the same capability of sensing and computing, and the energy consumed due to these two functions is small enough to be neglected [15], therefore they are unconcerned in our work.
- The task of this network is to gather the data from nodes and forward it to BS. We assume that the network is fault-free, i.e. the time delay, data loss and other serious system or communication fault are not considered.

When the nodes are randomly deployed, the first work for each node in the network is to seek the neighbor nodes. The unique ID and other status of the neighbor nodes will be recorded in a neighbor table [5], such as current residual energy, number of neighbors, alive or dead. Particularly, the energy consumption between the neighbored nodes can be obtained by self-calculating residual energy, which later is used in choosing CHs. The neighbor lists are essential for the network, for the subsequent procedures are based on neighbor tables. Nodes can be CMs or CHs, their status can change at different cluster set-up period. However, the physical relationship of neighbor nodes is fixed due to the stationary deployment. If some node dies, the ID will be eliminated from its neighbors' neighbor lists in order to save the unnecessary energy consumption.

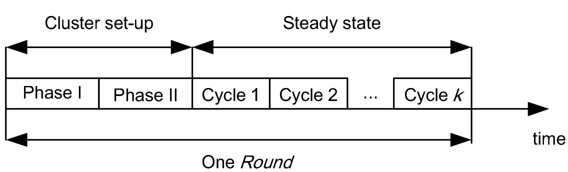

Fig. 1. One Round consists two periods, cluster set-up period and steady-state period. The former is divided into two phases, while the latter includes a number of cycles determined by *ECC* in Phase II.

We introduce the notation of *Round* to denote the lifetime of the cluster. As illustrated in Fig. 1, one *Round* starts from cluster set-up period and ends when the energy of CH has run out in the steady-state period. In the steady state period, we also present the notation of *cycle* as the time scale. In a *cycle*, for each cluster, a certain number length of data will be sensed by the CMs, forwarded to the CH where got compressed into fixed length, and then transmitted to BS. The same procedure can be applied in all the clusters. Actually, the numbers of *cycles* are obtained during the cluster set-up period by computing *ECC*. After selecting the CHs, clusters will be built up, and each cluster has one *ECC*, i.e. the number of *cycles*. Then minimal *ECC* is then adopted as the common *ECC* so that the procedures in all the clusters can be implemented simultaneously. One *cycle* represents the time consumed for the certain length of data communicating from sensing at CMs to forwarding to BS. We use *ECC*, i.e. the number of *cycles* as the time scale instead of time directly, because the time consumed for this CM-CH-BS procedure varies according to different background. And since the time for each procedure can be reasonably fixed, the real consumed time is proportional to the cycles. Also our work concerns the procedure itself and hence we take number of *cycle* as time scale to measure the lifetime of the network.

At the end of the steady state, the CH changes its role as a potential CM node, and intra-cluster relationship is disassociated. Then a new Round will be activated.

3.1 Two-Phase Cluster Set-Up Period

3.1.1 Phase I: CH Candidates Seeking

The purpose of this phase is to find out the CH candidates. Before deployment, the initial energy threshold e_{th} is predefined and embedded into every node. This threshold could simply be the energy mean of all the nodes alive in the network. As the work in [7], BS evolves to determine the residual energy threshold during the network lifetime. Also, it is altered before attempting of a new *Round*, i.e., in *Cycle k* shown in Fig. 1. At that moment, CHs gather the residual energy from their own cluster members, and forward the averaged value of residual energy to BS. Then BS computes the average residual energy for the network and sends it back to CHs. By intra-cluster communicating again, the CMs can know the new threshold.

This phase includes two steps, the establishment of *Temporary Clusters* and determining the CH candidates.

Temporary clusters (*TCLs*) will be initialized after the neighbor-table is built up. If a node has bigger residual energy ($e_{res} > e_{th}$), and has not heard the announcement of the clustering request from other *Temporary CHs* (*TCHs*), then it announces itself as *TCH* within the neighborhood after a random delay. Meanwhile, after receiving the *TCH*'s announcement, the neighbor nodes confirm by replying their own e_{res} and unique ID to the *TCH*. These neighbor nodes work as the *Temporary Cluster Members* (*TCMs*) with allocated temporary cluster addresses by the *TCH*. If some node happens to hear the announcement from more than one *TCH*, then at that stage it only replies to the closest *TCH* due to the relatively small energy consumption for both the *TCH* and itself. In this way, *TCLs* are established by *TCMs* and their *TCHs*. Herein the temporary cluster addresses are used to facilitate the clustering, which can be a serial number. If a node has had the temporary cluster address, it neglects the clustering request from other *TCHs*. On the other hand, these temporary addresses are more helpful than unique ID to enhance the cluster efficiency during the following intra-*TCL* communication. Furthermore, different to the fixed pre-allocated unique IDs, these *TCL* addresses are changeable. A node has only one unique ID, while during the network lifetime it can be assigned at least one temporary cluster address by different *TCHs* at different *Round*. But temporary addresses only exist in *TCLs*, and at each time, the node can have only one temporary address. Additionally in the case when the node acts as the *TCH*, then it allocates temporary addresses to itself and its *TCMs*.

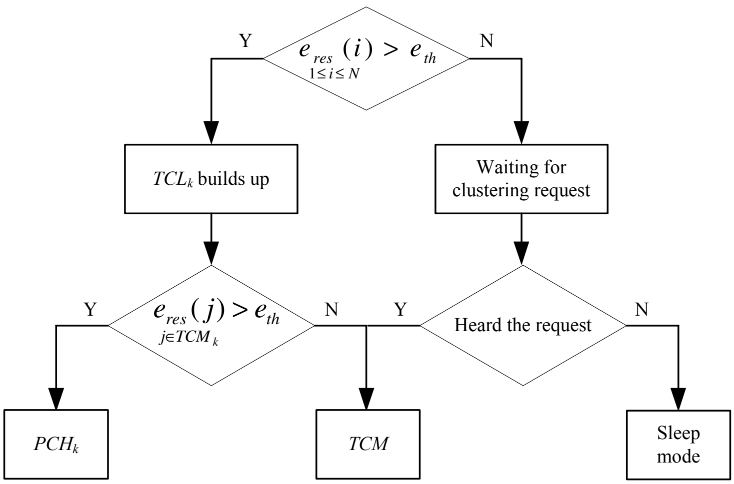

Fig. 2. Procedure of Phase I. It is based on the residual energy and the status of their neighbor nodes. The *TCLs* are built up for the further selection operations.

Within each *TCL*, the *TCMs* with the higher residual energy (than e_{th}) name themselves as *Potential CHs (PCHs)* and let the *TCH* know. However, *PCHs* don't need to establish their clusters, because the *TCH* in the *TCL* has been in charge of the communicating and managing before the final CH is settled down. Now *TCHs* and *PCHs* co-exit in the network, and both of them are regarded as CH candidates. The CHs will be selected among these candidates. Fig. 2 shows the procedure of this phase, where *N and n* respectively denote the number of nodes in the network and the number of CHs determined by the pre-defined density, while $e_{res}(i)$ means the residual energy of Node(i), TCM_k represents the set of *TCMs* in the *k-th TCL*, and j is the temporary address allocated by TCH_k. As the flow chart illustrated in Fig. 2, all the nodes are involved in the top decision box, while only the nodes with temporary address, namely, the *TCM* nodes, take part in the lower left residual energy comparison.

It also happens that the node has not heard any announcements after some period of time. In this case, it identifies itself as *TCH* if $e_{res} > e_{th}$. Otherwise, it falls into sleep mode and periodically wakes up to receive maintenance messages.

Once a *TCL* is established, the TCH then lets the BS know, such that the BS can count the number of *TCHs* in the network, which should be no more than *n*. If the number is larger than *n*, Phase I shall be ceased; on the other hand, if less *TCLs* are found, the BS reduces the eth and broadcasts it to the network to find the rest *TCLs*, however, the established *TCLs* can ignore this new broadcasting.

In this phase, CSMA-CA scheme is adopted when the distributed *TCLs* are talking to BS, as well as the intra-*TCL* communication. These *TCLs* facilitate the selection of *PCHs*. Otherwise, the network has to turn to BS to make the determination of the CH selection [7], and this could be a highly energy-consuming task. The values of *ECC* of these candidates will be self-computed and compared by the *TCHs*. This work will be done in Phase II.

3.1.2 Phase II: *ECC* Computing and Comparison

Phase II is responsible for seeking the qualified CHs by computing and comparing CH candidates' *ECC*. As defined in (2), *ECC* evaluates the times of data forwarding procedures that the CH candidate can make, i.e. the lifetime of the cluster. As shown in (2), the value of *ECC* is subject to its residual energy and the energy cost of a certain length data intra-*TCL* communication. The value of *ECC*, in fact evaluates the lifetime of the cluster steady-state period.

$$ECC(i) = |NBR_i| \frac{e_{res}(i)}{\sum_{j \in \{NBR_i\}} e_{NBR}(i,j)} \tag{2}$$

In (2), $\{NBR_i\}$ is the set of Node(i)'s neighbor nodes, $|NBR_i|$ is the number of nodes in this set, and $e_{NBR}(i,j)$ is the energy consumption between Node(i) and its neighbor node Node(j), as shown in (3) [1],

$$e_{NBR}(i,j) = e_{Tx}\left(l, d_{i,j}\right) + e_{Rx}(l) = l \cdot \left(2 \cdot e_{elec} + \varepsilon_{mp} \cdot d_{i,j}{}^2\right) \tag{3}$$

This equation is a model for one transmitting-receiving relay with a l-bit packet over distance $d_{i,j}$. In practice, as mentioned in Section 2, we can get this value by subtracting the residual energy before and after the l-bit length data communication relay, though in theoretical analyze, we still use (3) to evaluate the energy consumption. This consumption can be obtained in neighbor seeking period.

Firstly within a *TCL*, *PCH* nodes calculate their own *ECC* and transmit the values to the *TCH*. While the *TCH* also computes its own, then compares it with the received values from *PCHs*. Then the *TCH* will choose the node with highest *ECC* as the final CH, i.e. $CH(k)=\{\max\{ECC(g)\}|\ k \in [1,n],\ g \in [1,\ |TCH_k|+|PCH_k|]\}$, where n is the number of CHs in the network, based on the pre-defined density of CHs. $|TCH_k|$ and $|PCH_k|$ respectively means the number of *TCHs* and *PCHs* in the *k-th TCL*, namely, the number of CH candidates in the *k-th TCL*. The number of the selected CHs is subject to the pre-defined CHs density. Within the real cluster, the temporary addresses are deactivated, replaced by the CMs addresses which are allocated by the selected CH. Their pre-defined unique IDs are still reserved.

In the chart flow in Fig. 3, ECC_{k_max} means the maximal *ECC* in the *k-th TCL*. Meanwhile, we note that the number of *TCLs* is not relevant to the CH density. The communication between the *TCH*/CH with BS is based on CSMA-CA schedule.

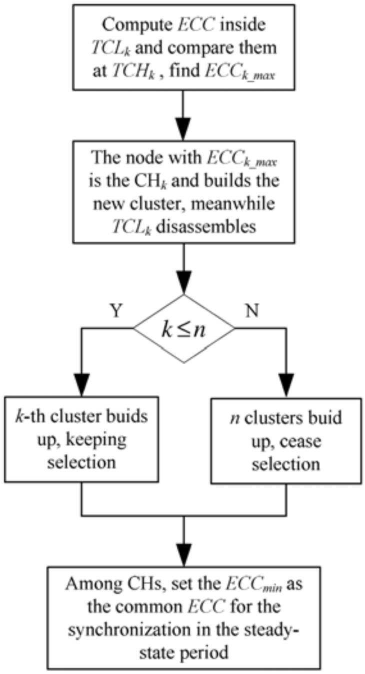

Fig. 3. Procedure of Phase II. Each CH candidate computes its own *ECC* and has it compared at *TCH*, such that the proper CH is selected with the common *ECC* for the synchronization.

Each *ECC* in the *TCL* is sent to BS by the selected CH, and minimum *ECC* among the selected *CHs* is determined by BS as the Common *ECC*. Then this value is forwarded to each CH, which is used in the steady state period, such that all the clusters can synchronize their work. CHs have to send an Acknowledge message back to BS before the synchronized steady state.

3.2 Steady State Period

In the steady-state period, basically three tasks are involved. Namely, the maintenance messages between CHs and their CMs, data sensing and communicating from CMs to the CHs, and lastly the compressed data [1] forwarding from CHs to BS, as illustrated in Fig. 4. During each cycle, l-bit data is gathered from each CM, forwarded to the CH, and finally sent to BS after compressing into a certain length at the CH. During this period, the intra-cluster communication is based on TDMA schedule.

Synchronization not only depends on the same *ECC*, and the same beginning time, but also relies on the time spent in each cycle. In our assumption, we assume the network is fault-free, hence in our work, we don't concern the fault that may occur during the network lifetime.

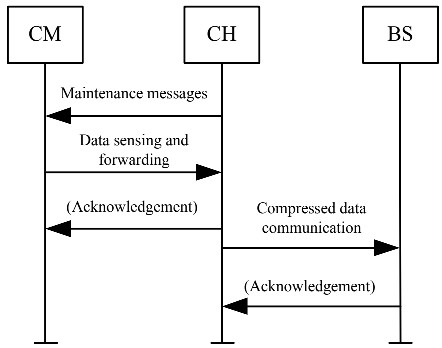

Fig. 4. Operations of nodes in a cycle. CMs forward the sensed data to the CH, the data are finally sent to BS after compression at the CH.

4 Simulations

Since LEACH is the classic protocol using CH rotating strategy, and DECP is a recent weight-based selection protocol, by respectively applying LEACH, DECP and ECHS, we compare the simulation results. With NS-2 [17], we build the WSN with 100 nodes randomly deployed in the flat area of 100 m ×100 m. The bandwidth of the channel is configured as 1 Mb/s. And as mentioned above, only *TCHs* and CHs use multipath fading (*mp* in Table 1), i.e. d^4 power loss model, and other nodes use Friss free space (*fs* in Table 1), i.e. d^2 power loss model [1]. Also similar with [7], the communication corruption due to noise is not considered in the simulation.

Herein, we compare ECHS with DECP because the similarity of these two method. The differences are not only the mutual-distances-based approach in DECP which might lead to flaw as mentioned in Section 2, but also the fact that in DECP, CH-selection procedure has every node involved in calculating the threshold, and this also increases the energy consumption. Though ECHS avoids these unnecessary procedures, the factor we concern in DECP is the one-phase methodology to choose CHs. One-phase selection might be able to save the overhead, compared to our two-phase method. But we realize that overhead is just one of the factors that could determine the lifetime. And in our simulation, overhead due to the two phases doesn't lead to the shortened lifetime, because we think the properly selected CHs are the key to the longer lifetime. In our work, we simulate LEACH, DECP and ECHS as well in order to demonstrate the network performance based on these three methods.

The values of main parameters are set to be the same for these three protocols, as shown in Table 1. Also, we assume that the values of the CH density in these protocols are as same as LEACH, which is 5% [1]. Also, we set the transmission range of all these nodes to be 25 m, which is less than the crossover range. And we fix BS at the bottom left corner of the node deployment, namely, (0, 0).

In general, the node is regarded as 'dead' when it depletes the energy. However, in fact, the life of node can be terminated when the residual energy is small enough to perform the whole procedure of communication. In this paper, we define a

Table 1. The radio characteristics used for three protocols are same in the simulation work

Operation	Energy Dissipated
Transmitter/Receiver Electronics	$E_{elec} = 50\ nJ / bit$
Crossover Distance	$d_0 = 87.7058m$
Transmit Amplifier, if $d < d_0$	$\varepsilon_{fs} = 10\ pJ / bit / m^2$
Transmit Amplifier, if $d \geq d_0$	$\varepsilon_{mp} = 0.0013\ pJ / bit / m^4$
Prorogation Loss, if $d < d_0$	$\alpha = 2$
Prorogation Loss, if $d \geq d_0$	$\alpha = 4$

terminating threshold e_{tt}, where $e_{tt} = e_{Tx}(l,d_0) + e_{Rx}(l) = l\cdot (2e_{elec}+ \varepsilon_{mp}d_0^2)$. Nodes can compare it with its own e_{res}. If $e_{res} \leq e_{tt}$, namely, it can't afford a l-bit data communication within the crossover distance, the node then can be regarded as a 'dead' node. Meanwhile, we also assume the lifetime of this network is terminated if the number of nodes alive in this network is below 20%.

In the simulations, since we are more attempting to simulate the energy-constrained WSN, herein the initial energy is not equal, but randomly defined between e_{tt} and 0.01J. The energy of 0.01 J here is small enough to be considered as the limited initial energy, which actually cuts the beginning lines in the simulation results in LEACH, only representing all nodes alive. Our simulation of initial energy implies that nodes could have been 'dead' since the beginning of the simulation. And we may not obtain the all-nodes-alive even line before descending, as many literatures do in their simulations [1], [13]. The simulation runs for 100 times.

In summary, we assume that each of the following case can terminate the simulation. Namely, less than 20% of the nodes alive or none CH found ($e_{th} \leq e_{tt}$), etc. The latter condition leads to one of the potential results that the network could be ended with some nodes (>20%) still alive. In this case, they don't have enough residual energy to communicate mutually in the neighborhood or build up the clusters.

Firstly, it apparently shows that in Fig. 5, ECHS has the longest lifetime, which is longer than LEACH by around 24% and DECP by 20%. Especially during mid-term of the lifetime, ECHS enables much more nodes alive than the other two do. This contributes to the more gather data. While DECP ends up the network with over twenty percent nodes alive, this is nearly twice as many as ECHS and LEACH.

We can also observe the efficiency of ECHS protocol in terms of the WSN global energy. As presented in Fig. 6 where the ECHS protocol based WSN has more global energy almost during the whole lifetime. Especially much more than the one that LEACH based WSN has. And for LEACH, the dive at 0.4×10^4 cycles is because of the randomly defined initial energy. Nodes deplete much faster than the other two protocols based WSNs.

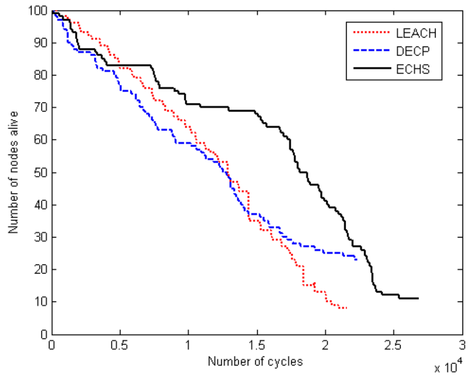

Fig. 5. Number of nodes alive based on these three methods differ during the lifetime

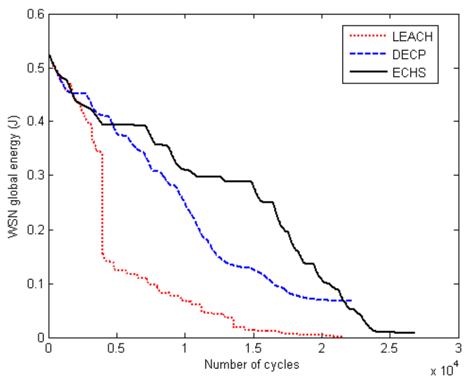

Fig. 6. WSN global energy changes during the lifetime, where the ECHS-based network performance is extraordinarily dominant

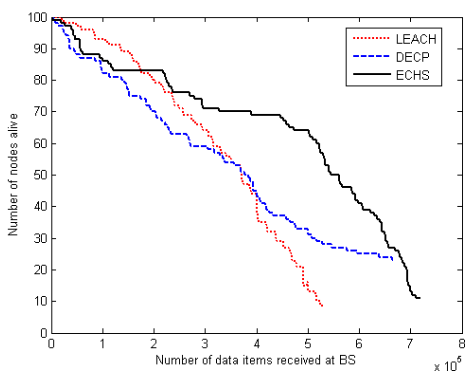

Fig. 7. Number of nodes alive and the number of data items received at BS. ECHS enables more data to BS and more nodes alive during the lifetime.

And lastly in Fig. 7, we compare the data received at BS. It shows that ECHS protocol contributes to more data sent to BS, especially in the second half of the lifetime. Respectively, based on ECHS, the amount of data transmitted to BS at last moment is nearly 7.5% and 36% more than DECP and LEACH.

These simulations contribute to the result that CHs are well chosen, and this leads to the high performance in longer lifetime and data items received at BS.

5 Conclusion

We focus our work on the energy-constrained WSNs and propose the *ECC*-based protocol to seek the suitable CHs. By dividing the CH selection into two phases, the appropriate CHs are selected respectively based on the high residual energy and the energy consumption cycle comparison. Especially in the second phase, the value of these energy consumption cycles in fact represents the longevity of clusters, which also evaluates the lifetime of the network. ECHS approach balances the energy consumption, prolongs the network lifetime and furthermore, increases the amount of data received at BS. As shown in the simulation work, ECHS protocol can be regarded as an efficient method for energy-constrained WSNs.

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