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Energy-balanced Parameter-adaptable Protocol Design in Cooperative Wireless Sensor Networks

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Abstract

The performance of Wireless Sensor Networks (WSNs) is adversely affected by the radio irregularity and fading effect. Cooperation is introduced into WSNs and serves as an effective way to combat fading effects. Meanwhile, sensor nodes having heavier burden than others result in the energy imbalance problem which remains harmful to the system lifetime.

In this paper, we design a protocol for cooperative WSNs with energy balance consideration. Since the design of WSNs is highly dependent on application scenarios, the effects of system parameters are thoroughly analyzed and a unified criterion is established to choose the proper cooperative scheme. Moreover, energy balance is achieved by adjusting the size of clusters. We classify energy consumption into two groups: inter-cluster energy consumption and intra-cluster energy consumption. Sensor nodes consuming higher energy in inter-cluster data communication form smaller clusters. Thus energy consumption is balanced between intra- and inter-cluster data communication. The proposed energy-balanced parameter-adaptable cooperative protocol (EBPACP) efficiently applies cooperation in cluster-based WSNs and balances energy consumption. A complete protocol design including the cluster formation, cooperative relationship buildup and data transmission are investigated thoroughly in this paper. Simulation results have shown that the proposed EBPACP provides good system performance in terms of energy efficiency and energy balance.

1. Introduction

A wireless sensor network (WSN) is composed of a large number of sensor nodes that are randomly and densely deployed in an area for the purpose of monitoring certain phenomena of interest. The nodes sense information, process the sensed data and transmit the processed data to the Base Station (BS) over a wireless channel. Nowadays, the rapid advances in hardware of sensors and network topology have addressed a wide range of potential applications of wireless sensor networks such as battle field surveillance, traffic control and environmental monitoring.

WSNs distinguish themselves from traditional networks in the following ways: energy constraints, large scale deployment and highly application dependence. On the other hand, as other wireless communications, data transmissions in WSNs have to go through fading channels for long distance transmission which is fundamentally impairment to the reliable and high-speed wireless communications.

The features of WSNs pose designers challenges as well as opportunities. Low Energy Adaptive Clustering Hierarchy (LEACH) protocol proposed in [1] is considered as one of the most fundamental and elegant protocol frameworks in literature. In LEACH, the sensor nodes are grouped into clusters and data are aggregated and transmitted to the BS by cluster heads

(CHs). The LEACH architecture is widely adopted in the research of WSNs [2,14]. However, adversely affected by the instable wireless channels, CHs dissipate a considerable amount of energy for long haul data transmission to the BS to combat the fading effect.

Diversity has been proven to be an effective way to combat fading effects by providing the receiver with several independent replicas of the transmitted signal [3,4]. It was pointed out in [5] that a Multi-input Multi-output (MIMO) system may support higher data rate without increasing transmission power. Alamouti discovered a remarkable space time block coding (STBC) scheme for transmission that can achieve full diversity with two antennas [6]. It was later generalized to an arbitrary number of antennas in [7]. However, in these schemes, multiple antennas are required, which is not practical for small-sized devices that can only afford one antenna. Cooperative transmission emerges as a way to help single antenna users to reap the benefits of diversity, which extend the application of MIMO to single antenna users.

Sendonaris *et al.* demonstrated in [8,9] that cooperative diversity not only increases the sum-rate over non-cooperative transmi1ssion, even though inter user channel is noisy, but also promises a more robust system where users' achievable rates are less susceptive to channel variations. The authors in [10] investigated the condition that MIMO system outperforms Single-input Single-out (SISO) systems and extended the work to an application in WSNs. In [11], the authors proposed a cluster-based cooperative MIMO scheme, which is called MIMO LEACH in the sequel of this paper. The criterion to choose the cooperative nodes was given in [11]. The authors formulated an optimization model to minimize system energy consumption by choosing the number of cooperative nodes and the number of hops to the BS.

Besides the work of how to achieve good performance in cooperative WSNs, effort has been made on the selection of optimal cooperative scheme according to different scenarios. In [12], an optimal selection of cooperative MIMO schemes is proposed based on the energy consumption for different transmit distances. However, in [12] only the impact of transmit distances was considered. A more thorough research is given in [13] on the topic of when cooperation has a better performance in WSNs. Impacts of system parameters such as requirement of QoS are analyzed. However, the work of [13] was mainly about how a single parameter changes the advantages of protocols and the analysis is limited to cooperation between two nodes. In case of two or more parameters change, the selection of the proper cooperative scheme remains unexplored.

Moreover, energy imbalance problem exists as a thread to long-lifetime WSNs and has attracted much research attention in recent years. It has been widely researched in non-cooperative WSNs but only a little work has been done when cooperation is applied in WSNs. In [14] the energy balance is considered in a cooperative cluster-based WSNs, but the authors only carry out numerical analysis. Although cooperation contributes to energy balance to some extent by decreasing the transmit power and share the transmitting responsibility among more nodes as pointed out in [15], the energy imbalance problem resulted from the different energy consumption of sensor nodes still exists and harms the performance of WSNs.

In our work, we try to reveal the impacts of system parameters by carrying out a thorough analysis of how system performance changes with parameters. A unified criterion is established to choose the preferred cooperation scheme such as when and how to cooperate in

WSNs. This criterion serves as a basis of our proposed protocol and adapts the protocol to the changes of system parameters. Also, energy balance is a main consideration in our design.

The following of this paper is organized as below. Section 2 analyzes the impacts of system parameters and establishes the unified criterion to choose the preferred transmission scheme. Section 3 describes in detail about the proposed Energy-Balanced Parameter-Adaptable Cooperative Protocol (EBPACP). Section 4 analyzes the energy consumption of EBPACP. Section 5 presents the simulation results and section 6 concludes this paper.

2. Impacts of system parameters

2.1. System Model

Energy model proposed in [10] is adopted in this paper. It uses link margin theory and breaks transceiver circuits into blocks to analyze energy consumption. The total power consumption along the propagation path can be divided into two parts: the power consumed by the power amplifier P_{PA} and power consumed by the circuit blocks Pc which breaks into two parts: transmitter circuit P_{ct} and receiver circuit P_{cr}. The former component P_{PA} is dependent on the transmit power P_{out} which can be calculated according to the link budget relationship [16].

$$P_{out}(d) = P_r \times \frac{(4\pi)^2 d^{\kappa}}{G_t G_r \lambda^2} M_l N_f \tag{1}$$

where G_t and G_r are the gains of transmitting and receiving antennas respectively, λ is the wavelength of the carrier signal, κ is the path loss index, d is the distance between transmitter and receiver, M_l is the link margin, N_f is the receiver noise figure defined as $N_f = N_r/N_0$ with N_0 the single-sided thermal noise power spectral density (PSD) at the room temperature and N_r the total effective noise at the receiver input, P_r is the required power per bit at the receiver output and can be calculated by $P_r = \gamma B N_0 N_f$ with γ the required signal to noise ratio (SNR) at the receiver to satisfy a specific BER requirement denoted as P_b, and B is the bandwidth.

The power consumption of the power amplifiers can be approximated as

$$P_{PA} = (1+\alpha)P_{out} \tag{2}$$

where $\alpha = \xi/\eta - 1$ is the efficiency of power amplifier with η the drain efficiency of the RF power amplifier and ξ the peak-to-average ratio (PAR). The PAR is dependent on the modulation scheme and the associated constellation size [17].

The energy consumption for transmitting and receiving one bit information can be written as

$$\begin{cases} E_t = (P_{PA} + P_{ct}) / R_b \\ E_r = P_{cr} / R_b \end{cases} \tag{3}$$

When cooperation is applied, the cooperative nodes first receive the transmitted information and then transmit it to the destination cooperatively. For a specific application when there are J cooperative nodes, the energy consumption can be written as

$$E_b(J,d) = (1+\alpha)\frac{J\bar{\gamma}(J)(4\pi)^2}{RG_tG_r\lambda^2} N_0 M_l N_f d^{\kappa} + \frac{JP_{ct}}{RR_b} + \frac{JP_{cr}}{R_b} \qquad (4)$$

where $\bar{\gamma}$(J) is the average required SNR at the receiver for a targeted P_b with J cooperative nodes and R is the code rate. It should be noticed that when cooperation is applied, γ(J) is greatly reduced compared with non-cooperation. And the more cooperative nodes, the smaller γ(J) is. Table 1 lists required γ(J) under different BER requirement, P_b, when different cooperative nodes are used.

Table 1. SNR requirement over Rayleigh fading channel [16]

Number of nodes \ **Pb**	**10^{-2}**	**10^{-3}**	**10^{-4}**	**10^{-5}**
Direct (no cooperation)	14 dB	24 dB	34 dB	44 dB
J=2 (two nodes cooperation)	9.5 dB	14 dB	19 dB	24 dB
J=3 (three nodes cooperation)	8.9 dB	12 dB	15 dB	18.7 dB

Table 2. System Parameters [10]

$P_b = 10^{-3}$	N_f = 10 dB	N_0 = -174 dBm/ Hz
$G_t\ G_r$ = 0.5 dBi	f_c = 2.5 GHz	α = 1.47
R_b = 10 kbps	P_{ct} = 98.2 mW	P_{cr} = 112.6 mW
M_l = 40 dB	$\kappa = 3$	R =0.5

2.2. Analysis of Parameter Impacts

From Eq. (4) and Table 1, we observe that the energy consumed by power amplifier decreases but circuit power consumption increases with the increase of cooperative nodes. It is pointed out in [10] that cooperation is not always beneficial and there is a distance threshold to it. In regard to how many cooperative nodes should be applied, it is also determined by whether the energy saved from cooperation exceeds the overhead in circuit consumption.

The system parameters like P_b, α, *etc*, have significant impacts on the energy consumption in amplifier or circuit. We group the parameters into three groups by their impacts on the energy consumption.

- Parameters that affect circuit energy consumption: R_b, P_{ct} and P_{cr}.
- Parameters that affect amplifier energy consumption: α, P_b, κ, N_0.
- Parameters that affect both: J and R.

In our analysis, we use the parameters listed in Table 2, which have been widely adopted in the literature. We vary one of the system parameters but keep the rest of them fixed to observe the impacts of the chosen parameter.

In order to compare the performance of cooperation, we define Cooperation Gain (CG) as a criterion to quantize the performance. CG measures the energy saved by cooperation over non-cooperation and is defined as:

$$\mathit{Cooperation\ \ Gain}\quad (CG)=\frac{e_{non}-e_{coop}}{e_{non}} \tag{5}$$

where e_{non} is the energy consumption of non-cooperative transmission and e_{coop} is the energy consumption of cooperation. From the definition of CG we observe that CG is a number less than 1 and different ranges indicate the contrast of cooperative transmission and non-cooperative transmission. The bigger CG is, the more energy is saved from cooperation.

- CG > 0: Cooperative transmission outperforms non-cooperative transmission.
- CG = 0: Cooperative transmission equals to non-cooperative transmission.
- CG < 0: Cooperative transmission is worse than non-cooperative transmission.

We present the impacts of P_b and R_b as examples in the following figures. The preferred cooperation scheme varies with the changes of the system parameters.

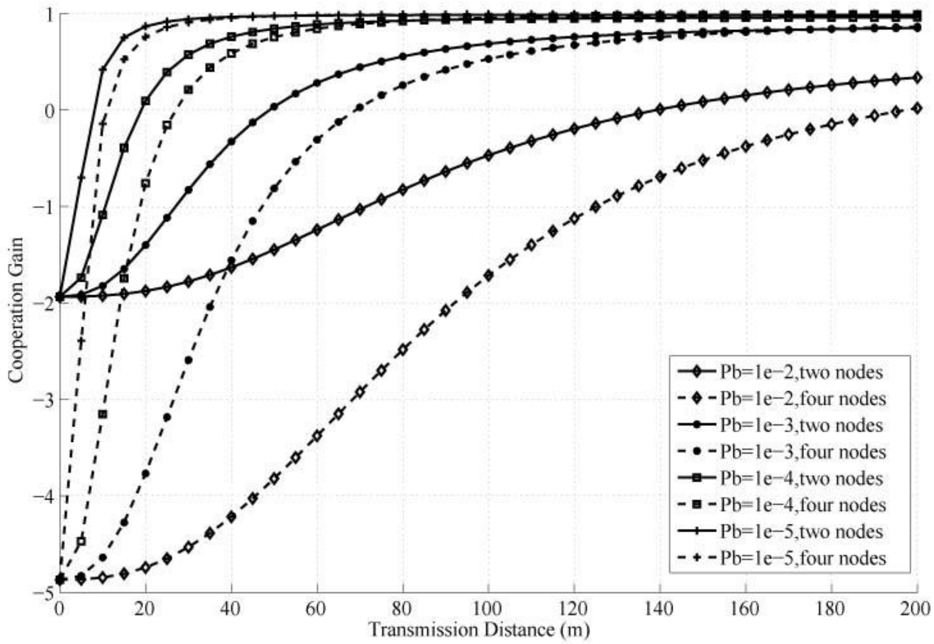

Fig. 1. The impacts of BER requirements

Fig. 1 shows how CG changes with the requirement of BER. When BER requirement is higher, cooperation outperforms non-cooperation at a relatively short distance. Like for BER requirement of $P_b = 10^{-3}$ cooperation is more energy efficient when transmit distance exceeds

50 m but for $P_b = 10^{-2}$, the threshold distance is 140 m. The CG of four cooperative nodes is smaller than that of two cooperative nodes when transmission distance is short. But this difference becomes smaller with the increase of transmit distance. This indicates that with the increase of transmit distance, power dissipated in amplifier increases and more cooperative nodes are preferred.

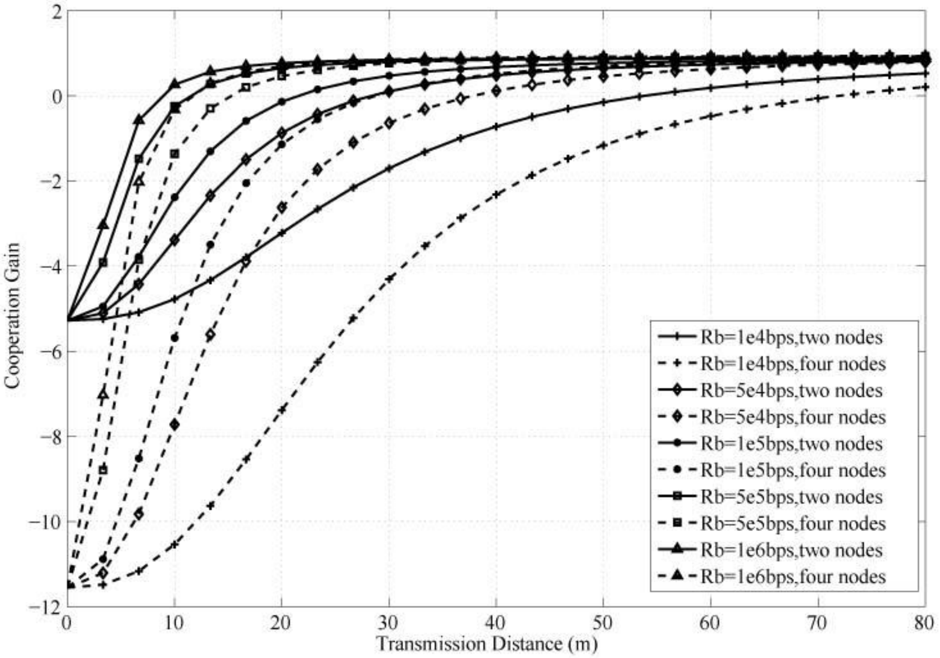

Fig. 2. The impacts of bit rate

Bit Rate (R_b) has a significant impact on the energy consumed by the transceiver circuits. As shown in Fig. 2, less energy is consumed in transceiver circuit for higher R_b, and therefore cooperative transmission is preferred at a relatively short distance.

From our analysis of the impacts of system parameters, we observe that how parameters affect the advantages of cooperation is related to whether they affect amplifier or circuit power, which can be observed from Figs. 1 and 2. If the changes of parameters increase the amplifier power, it will stress the advantage of cooperation. On the other side, if the change of the parameter increases circuit power consumption, it stresses the advantage of non-cooperation. Hence it comes to the conclusion that the ratio of amplifier power over the circuit power determines whether cooperative transmission outperforms non-cooperative transmission or not and how many cooperative nodes should be used.

2.3. Criterion to choose the preferred cooperation scheme

Based on the conclusion of impacts of system parameters, we define two coefficients: amplifier power coefficient C_a and circuit power coefficient C_c. They are related to the amplifier power and circuit power respectively and are given as

$$C_a = (1+\alpha)\frac{(4\pi)^2}{RG_t G_r \lambda^2} M_l N_0 N_f \tag{6}$$

$$C_c = \frac{P_{ct}}{RR_b} + \frac{P_{cr}}{R_b} \tag{7}$$

With the definition of Ca and Cc, we rewrite (4) as

$$E_b(J,d) = C_a J \gamma(J) d^{\kappa} + JC_c \tag{8}$$

where J = 1 denotes non-cooperative transmission. In order to explore the performance of cooperation, we simulate the energy consumption from J = 1 to J = 10. The ratio of amplifier power coefficient C_a over circuit power coefficient C_c varies from 3.5×10^{-7} to 3.5×10^{-2}. Table 3 presents an example of the preferred number of cooperative nodes for different transmit distances and ratios of C_a over C_c.

Table 3. The Optimal Number of Cooperative Nodes

Distance C_a / C_c	20m	30m	40m	50m	60m	70m	80m	90m	100 m
3.5×10^{-7}	1	1	1	1	2	2	2	3	4
3.5×10^{-5}	1	1	2	2	3	3	4	5	5
3.5×10^{-4}	2	2	2	3	4	4	5	5	5
3.5×10^{-3}	2	2	3	4	5	5	5	5	5
3.5×10^{-2}	2	3	4	4	5	5	5	5	5

The ratio of C_a over C_c can be treated as the unified criterion to choose whether cooperation or not and the number of cooperative nodes, and it will serve as a basis for our proposed EBPACP to choose the proper cooperation scheme.

3. Design of EBPACP

The proposed EBPACP is a hybrid protocol which applies both traditional clustering infrastructure and cooperative transmission into WSNs. In EBPACP, sensor nodes organize themselves into clusters and each cluster has a cluster head (CH). Sensor nodes firstly transmit data to the CH where local data processing is performed according to the application requirements. Then CHs will form a cooperative relationship and send data to the BS cooperatively. The operation of EBPACP is divided into rounds with an initial phase at the very beginning of the operation when some global information is shared between the BS and sensor nodes. Each round starts with a set-up stage during which CHs are elected, clusters and cooperative relationships are formed. This is then followed by a data transmission stage when the CHs collect data from their members, aggregate the data and then communicate with the BS.

Energy Balance is also considered in the design of EBPACP. We classify the energy consumption into two groups: inter-cluster energy consumption which corresponds to energy spent to communicate with other clusters as well as with the BS, denoted as E_{out}, and intra-cluster energy consumption which include energy spent in data communication inside the cluster as well as data processing like data aggregation, denoted as E_{in}. With the help of weighted distance, EBPACP balances energy by adjusting the sizes of clusters to compensate the energy differences in inter- and intra- cluster energy consumption. Sensor nodes have higher burden in inter-cluster data communication have longer weighted distance and therefore smaller cluster size. The operation of EBPACP is explored in the following.

3.1. Initial Stage

After the sensor nodes are deployed randomly, some global information should be shared among the sensor nodes and the BS. The BS collects the information about locations and energy levels of all the sensor nodes and sensor nodes are informed the location of the BS. And an estimated preferred number of cooperative nodes is calculated according to the criterion established in Section 2.3 for each node at its location. Each sensor node is assigned a node_ID i which is an integral number from 1 to N given N sensor nodes in the WSN.

3.2. Set-up Stage

The set-up stage of EBPACP has three steps: CH selection, cluster formation and cooperative relationship buildup. In EBPACP, we maintain the idea of rotating CHs. It balances the energy consumption among all the sensor nodes since they take turns to take the responsibility of CHs which is energy consuming. EBPACP further balances the energy by adjusting the size of clusters to balance intra-cluster and inter-cluster energy consumption. Moreover, EBPACP focuses on the selection the proper cooperation scheme with the criterion established in the previous section, which helps to achieve energy efficiency and the adaptability to the changes of environment.

3.2.1. First Stage: Cluster Head Selection. CHs are expected to spread evenly across the whole network and have enough remaining energy since being CH is quite energy-demanding. In order to achieve evenly distribution of CHs, the idea of reference points (RPs) is adopted in EBPACP. The whole area is divided equally into K regions and each reference point is the center of associated region. With the help of RPs, it is possible to meet the requirements that the CHs are distributed evenly, the shape of the clusters is regular and the sum of power consumption is small [18]. Actually these reference points are the preferred locations of the CHs. The WSN is divided geographical evenly into K regions and the RPs are the centers of the regions. Each RP is assigned an ID k, a number from 1 to K. k is also the ID of the CH selected for RP k and the associated cluster.

Since the CH is the most energy consuming node, sensor nodes selected as CH should have enough energy. Also, CHs should be located close to the RFs. We assign each sensor node a competition factor taking both distances to the RP and the remaining energy into consideration. The competition factor is denoted as $\zeta(i, k)$ for sensor node i to compete to be CH around reference point k. The competition factor ζ is defined as:

$$\varsigma(i,k) = \left(0.5 \times \frac{d_{rp}(i,k) - \min(d_{rp}(k))}{\max(d_{rp}(k)) - \min(d_{rp}(k))} + 0.5 \right) \times E_{re}(i) \tag{9}$$

where $E_{re}(i)$ is the remaining energy of node i, $d_{rp}(i, k)$ is the distance from sensor node i to RP k. $\min(d_{rp}(k))$ and $\max(d_{rp}(k))$ are the minimum and maximum values of distances from sensor nodes to reference point k respectively. Sensor nodes compete with each other by sending the value of ζ to the BS. The sensor node with the highest ζ value for reference point k is selected as the CH. Then the BS will inform all the sensor nodes the selected CH and then goes to the next stage of cluster formation.

3.2.2. Second Stage: Cluster Formation. If a sensor node is chosen as a CH, it will keep broadcasting an advertisement to the whole network to attract sensor nodes to join it using a fixed broadcasting power which is the same for all the CHs. The non-CH sensor nodes can estimate the distances to all CHs and keep these distances in $d_{ch}(i, k)$ as sensor node i to CH k. Then each sensor node chooses the closest CH and sends a joining message conveying its node ID. The CH k counted the number of its cluster members Num(k) and sends the information to the BS. The first step of cluster formation is finished, but EBPACP will adjust this formation based on an energy balance principle. For those CHs have higher burden in inter-cluster data communication, they have greater weighting factor which corresponds to longer weighted distances from sensor nodes to them. Therefore, less sensor nodes will join them and a smaller cluster is formed.

There are two weighting factors which are associated with two causes of energy imbalance. The first weighting factor is defined as

$$C_1(k) = \frac{Num(k) - \min(Num)}{\max(Num) - \min(Num)} \tag{10}$$

where k is the ID of the cluster, min(Num) and max(Num) are the minimum and maximum numbers of member nodes in clusters. This weighting factor is designed to reduce the different receiving energy of the CHs. In this case, clusters with more sensor nodes will have a higher burden on the cluster heads. From the definition of parameter C_1, we observe that C_1 is a normalized value from 0 to 1 and $C_1(k) \propto Num(k)$. The more sensor nodes a cluster has, the larger C_1 is.

On the other hand, energy imbalance problem is resulted from the different energy consumption in inter-cluster data communication. For example, in multi-hop system, sensor nodes close to the BS have to transmit data for those far from the BS, and therefore run out of energy earlier than those distant nodes. By contrast, in single-hop system, sensor nodes far from the BS dissipate more energy because of the long transmission distance, and they are prone to die earlier than those close nodes. Therefore, the second coefficient, C_2, is proportional to the energy consumed in inter-cluster data communication and is defined as

$$C_2(k) = \frac{E_{out}(k) - \min(E_{out})}{\max(E_{out}) - \min(E_{out})} \tag{11}$$

where $E_{out}(k)$ is the energy consumption for CH k in inter-cluster data communication. In single-hop system, $E_{out}(k)$ is the energy consumption for CH k to communicate with the BS. While in multi-hop system, it is energy consumption to transmit data to the next hop.

Then the BS sends these two weighting factors C_1 and C_2 of the CHs to all the sensor nodes. Each sensor node will calculate the weighted distances to all the CHs based on the following formula,

$$d_{ch2}(i,k) = (m_1 C_1(k) + m_2 C_2(k) + m_3) \times d_{ch}(i,k) \tag{12}$$

where $d_{ch2}(i, k)$ is the weighted distance between the sensor node i and cluster head k, m_1, m_2 and m_3 are constant coefficients between [0,1] with the constraint that $m_1 + m_2 + m_3 = 1$. If $m_1 = m_2 = 0$, it is the same as the geographical distance. m_1, m_2 and m_3 reflect the weight of each factor and should be carefully chosen to achieve a good system performance. Generally m_3 counts for the geographical distance and cannot be set to 0. m_1C_1 remedies the defect of uneven sensor deployment problem and m_2C_2 leads to unequal cluster size to balance energy.

With the weighted distance, each sensor node chooses their closest CH by sending a joining message. After each CH receives all the joining information from its members, it will create a TDMA schedule for its members to communicate with it and sends this information back to all its members. The cluster formation is finished at this time.

3.2.3. Third Stage: Cooperative Relationship Formation. In EBPACP, the cluster heads, instead of cooperative nodes inside one cluster, form a cooperative relationship to communicate with the BS together, which is also adopted in [19]. For the ideal coop-relation buildup, cluster heads grouped together are expected to be close to each other and share the same preferred number of cooperative nodes. This may not be feasible since the preferred number of cooperative nodes varies for different nodes.

Since an ideal formation is infeasible, we turn to suboptimal formation which is easier but also maintain a good performance. The number of preferred cooperative nodes is determined by the distance to the BS and the ratio of amplifier power over circuit power. For the sensor nodes in one WSN, we can treat the ratio of amplifier power over circuit power the same for all the sensor nodes since they share the same system parameters. Therefore, the only factor that determines the preferred number of cooperative nodes is the distance to the BS. For cluster heads that close to each other, their preferred numbers of cooperative nodes either equal to each other or vary a little bit as we observe from Table 3. Therefore, the BS will group the cluster heads close to each other together with the condition that the number of cluster heads in one coop-relation is close to the average preferred number of cooperative nodes. The formation of cooperative relationship is in Fig. 3.

3.3 Data Transmission Stage

At the data transmission stage, sensor nodes send data to the cluster heads where data aggregation is taken place. Then the cluster heads share the aggregated information with their cooperative partners and create STBC codes for cooperative transmission.

The cluster heads that are responsible for long-haul data transmission communicate with the BS in a cooperative manner. Fig. 4 shows the operation of data transmission.

3.3.1 Local Data Transmission. At the local data transmission stage, each sensor node wakes up from sleep mode at the beginning of its allocated time slot. It sends data to its cluster head and then turns off its radio components and goes back to the sleep mode again to save energy. After a cluster head collects all the information from its cluster members, it performs data aggregating. The ratio of data aggregation is dependent on application scenarios and correlation of the information among sensor nodes. Then it will broadcast a ready message to inform its partner cluster heads that it is ready to go on to cooperative transmission.

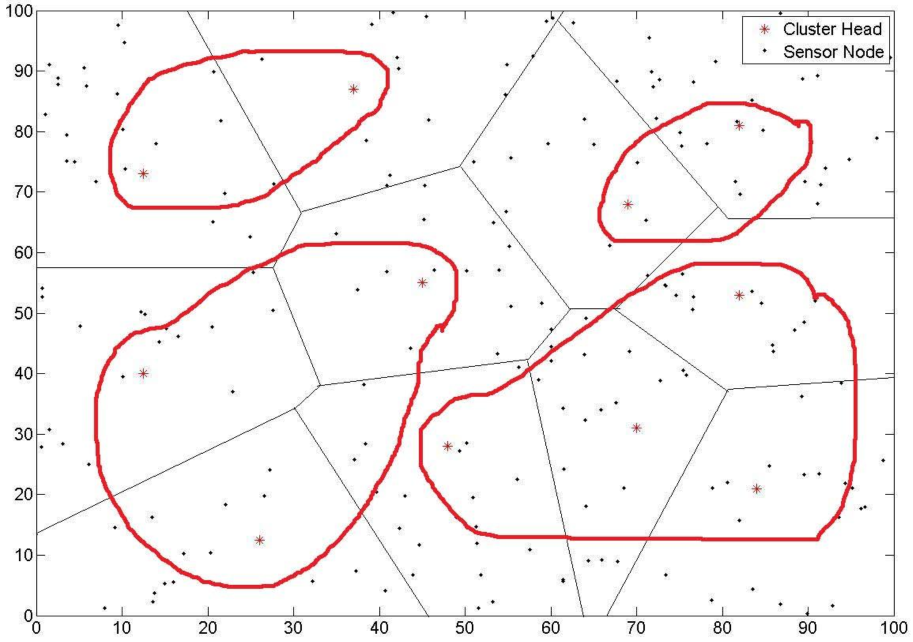

Fig. 3. Cluster Cooperative Relationship Formation

3.3.2 Cooperative Data Transmission. Generally there are three cases in the cooperation stage. The cluster heads in one region take different measures to cooperation.

Case 1: The number of region members is smaller than the average number of cooperative nodes. The CHs will choose some of their cluster members to get involved in cooperative transmission. The criterion for choosing cooperative nodes is given as

$$\varphi(i) = \frac{E_{re}(i)}{E_{out}(i)} \tag{13}$$

where $E_{re}(i)$ is the remaining energy for node i and $E_{out}(i)$ is the energy required for node i in inter-cluster communication given preferred number of cooperative nodes at the system BER requirement. Sensor node with the highest φ will be chosen as the cooperative nodes.

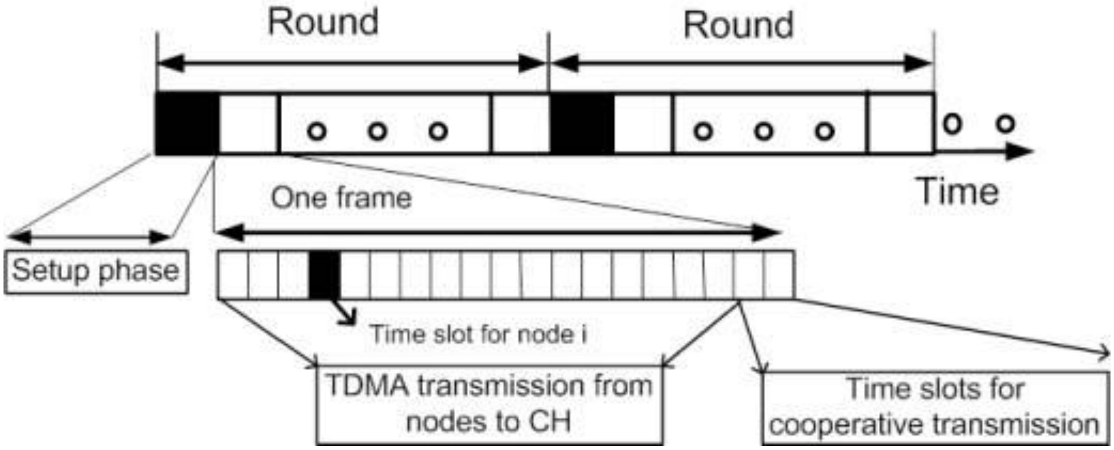

Fig. 4. Data Transmission

Case 2: The number of region members equals to the average number of cooperative nodes. This is the preferred situation so that all these cluster heads in one region will participate in the cooperative transmission.

Case 3: The number of region members is larger than the average number of cooperative nodes. Cluster heads with the highest φ values are chosen to participate in the long-haul transmission. The definition of φ is the same as in Equation (13).

Once the CHs receive all the ready messages from their cooperative partners, they start the cooperative transmission. First of all, they broadcast their data at the allocated time slot to share their information with all the other cooperative nodes which is also applied in [10]. The STBC codes are created to communicate with the BS. Whether further data aggregation is needed or not depends on application scenarios and the degree of redundancy among the information. When the cooperative transmission is completed, one frame ends; and another frame starts with local data transmission again. When a round is over, the network will start another round beginning with CH selection again.

4. Energy Consumption Model of EBPACP

Energy consumption of EBPACP is sorted into three categories: non-CH sensor nodes, cluster heads and cooperative nodes.

Energy consumption for non-CH nodes: For the non-CH nodes, they wake up at their allocated time slot and send the sensed data to the BS. Since this is intra cluster data transmission, we assume AWGN channel with a path loss index of κ_1 given that the signal propagation channel is relatively good. No cooperation is used in this stage. For simplicity, we first define ε as

$$\varepsilon = (1+\alpha)\frac{(4\pi)^2}{G_t G_r \lambda^2} N_0 M_l N_f \tag{14}$$

Given each message has l bits, the energy consumption for each sensor node i is:

$$E_{sn}(i) = l\varepsilon\gamma_{AN} d_{ch}^{\kappa 1} + l\frac{P_{ct}}{R_b} \tag{15}$$

where d_{ch} is the distance from sensor nodes to the cluster head and γ_{AN} is the required SNR under AWGN channel.

Energy consumption for CHs: Although the CHs are also responsible for data transmission to the BS, at this step we only consider the energy they spent on data collection and aggregation. For a cluster with T members, the energy consumption for the cluster head is

$$E_{CH} = Tl\frac{P_{cr}}{R_b} + TlE_{agg} + p \times l_r\left(\varepsilon\gamma(1)D^{\kappa 2} + \frac{P_{ct}}{P_{cr}}\right) \tag{16}$$

where $\gamma(1)$ is the SNR without cooperation under Rayleigh fading channel with path loss index κ_2, the first component is energy for receiving data, the second component is energy used in data aggregation with E_{agg} the energy consumption per bit per message in data aggregation, and the last component is energy dissipated in broadcasting ready message to its coop-partners given the message is l_r bits long and repeated p times with a wide broadcasting distance of D.

Energy consumption for cooperative nodes: In cooperative transmission, firstly each node broadcasts its data in the allocated time slot and listens to others during the rest time slots. Let D_{max} denote the maximum distance between cooperative nodes, the energy consumption for each cooperative node is

$$E_{coop} = l\left(\varepsilon\gamma(1)D_{\max}^{\gamma 2} + \frac{P_{ct}}{R_b}\right) + (J-1)l\frac{P_{cr}}{R_b} + l\left(\frac{\varepsilon\gamma(J)d_{BS}^{\kappa 2}}{R} + \frac{P_{ct}}{R_b R}\right) \tag{17}$$

where $\gamma(J)$ is the SNR threshold under Rayleigh fading channel for J cooperative nodes, R is the code rate.

4.1. Optimal Number of Clusters

In [1] the authors gave the algorithm to calculate optimal number of clusters based on the energy efficiency principle, which is mainly dependent on the network size like coverage area and number of sensor nodes, the ratio of energy consumed in long-haul data transmission and intra-cluster data transmission. Since cooperation has changed the energy consumption as well as the roles of the sensor nodes, the energy consumption is more complicated and the optimal number of clusters has also changed in cooperative WSNs. In the following, we set up an optimization model to find out how to determine the optimal number of clusters. For a region of M m × M m with N sensor nodes randomly distributed, we assume the number of clusters is K and clusters are grouped into X groups to cooperate. Combining (15) to (17), the total energy consumption to transmit a message of *l* bits to the BS in WSN can be written as

$$E_{total} = \sum_{i=1}^{N} E_{sn}(i) + \sum_{k=1}^{K} E_{CH}(k) + \sum_{x=1}^{X} E_{coop}(x) \tag{18}$$

Based on (18), the optimal number of clusters K is the one that minimize the total energy consumption in a WSN. It can be formulated as

$$K_{opt} = \min_{K} \quad E_{total}(K) \tag{19}$$

In order to find the optimal number of clusters, we use the same algorithm proposed in LEACH [1], but the energy consumption for sensor nodes are different from traditional LEACH since cooperation is involved.

5. Simulation Results

Our simulation is carried out in a single-hop system. 500 sensor nodes are randomly deployed in a region of 100 m × 100 m. The BS is located at [50, 200]. Each of the sensor node begins with 50 J initial energy and has a packet of 2000 bits to transmit at each frame. When nodes run out of their energy they can no longer transmit or receive message. We assume when 80% of the sensor nodes die, the WSN is considered out of service or dead. We assume the transmission is information lossless at the targeted BER requirement, the effective packets received at the BS is the number of packets transmitted by the source nodes. In our simulation, only data inside one cluster are aggregated and no more aggregation is carried out for cooperative data. However, in some application scenarios, there is still room for data aggregation in the cooperative transmission stage. In those cases, EBPACP will promise even more energy conservation since cooperation takes place among clusters instead of sensor nodes inside one cluster and data redundancy among clusters will be further removed.

Fig. 5 shows the number of nodes alive over rounds. It demonstrates that MIMO LEACH and EBPACP prolong the system lifetime greatly compared with LEACH, which indicates that cooperative transmission in WSNs is beneficial in terms of system lifetime. EBPACP prolongs the system lifetime even longer, about 22.5% improvement compared with MIMO LEACH.

However, the system lifetime is not the only yardstick to measure the performance of WSN protocols. The effective packets that arrive at the BS count a lot in the choices of different schemes. Fig. 6 shows the number of effective packets received by the BS and Fig. 7 shows the number of nodes alive versus effective packets received by the BS. Both of the figures demonstrate the advantages of EBPACP over LEACH and MIMO LEACH. Since the system lifetime is greatly increased by EBPACP, more time is allowed for EBPACP to transmit data to the BS, and therefore the number of effective packets received by the BS is increased. As shown in Figs. 6 and 7, EBPACP has the best performance out of the three.

Fig. 8 shows the remaining energy over the effective packets received at the BS. It is more energy efficient if cooperation is applied as MIMO LEACH and EBPACP all consume less energy for a certain amount of packets transmitted to the BS than LEACH. For a certain amount of packets arrived at the BS, LEACH consumes the most energy while EBPACP uses the least energy.

Fig. 9 gives a comparison of energy consumed by the sensor nodes close to or far from the BS respectively. We keep a track of the energy consumption of 10 closest sensor nodes and 10 most distant sensor nodes during each round. The histogram shows the difference between close nodes and distant nodes in WSN. Since in EBPACP, energy balance is considered in the design, the energy differences are greatly reduced. Both MIMO LEACH and EBPACP reduce the energy differences compared with LEACH, which indicates that cooperation contributes to the energy consumption. Because when cooperation is applied, the energy consumed by close and distant sensor nodes is greatly reduced. Consequently the differences in energy between close and distant sensor nodes are reduced. However, the energy imbalance problem still remains even cooperation is used. The sensor nodes far from the BS still dissipate more energy to communicate with the BS than close nodes, and this difference will affect the lifetime of WSNs. As shown in Fig. 9 that distant sensor nodes consume much more energy than close sensor nodes in MIMO LEACH. In EBPACP the differences are dwindled since energy balance is considered. Those cluster heads consuming more energy to communicate with the BS have smaller cluster size. As a result, the energy saved from intra-cluster data receiving and aggregating compensates for long-haul transmission energy consumption.

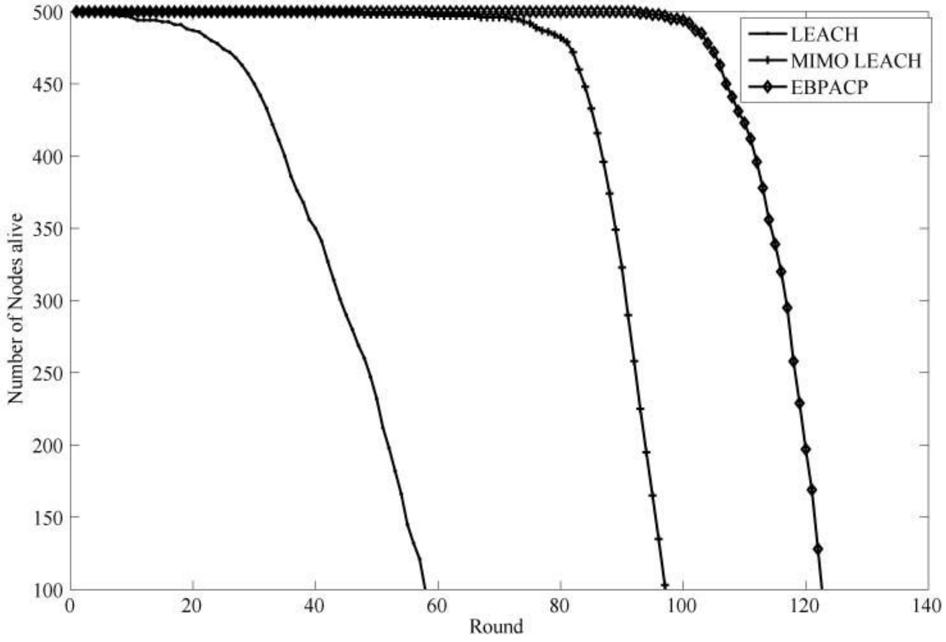

Fig. 5. Number of Nodes Alive over Rounds

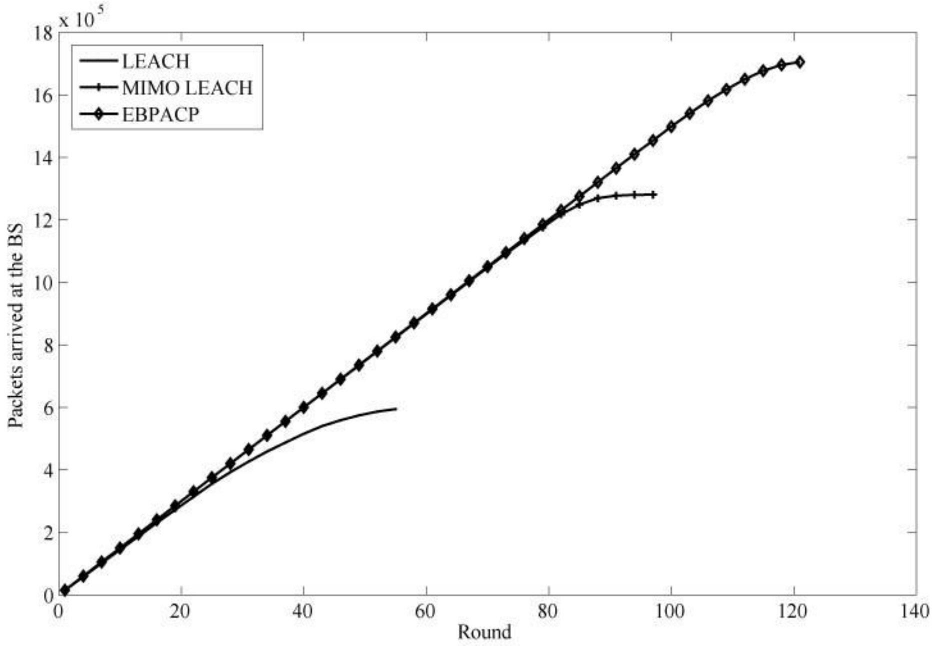

Fig. 6. Packets arrived at the BS

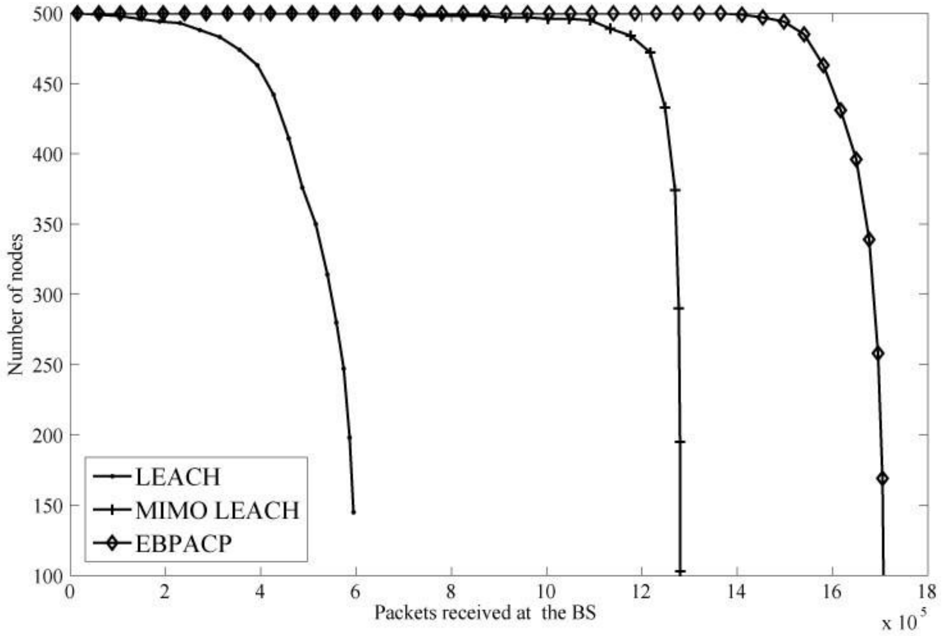

Fig. 7. Number of alive nodes vs packets arrived at the BS

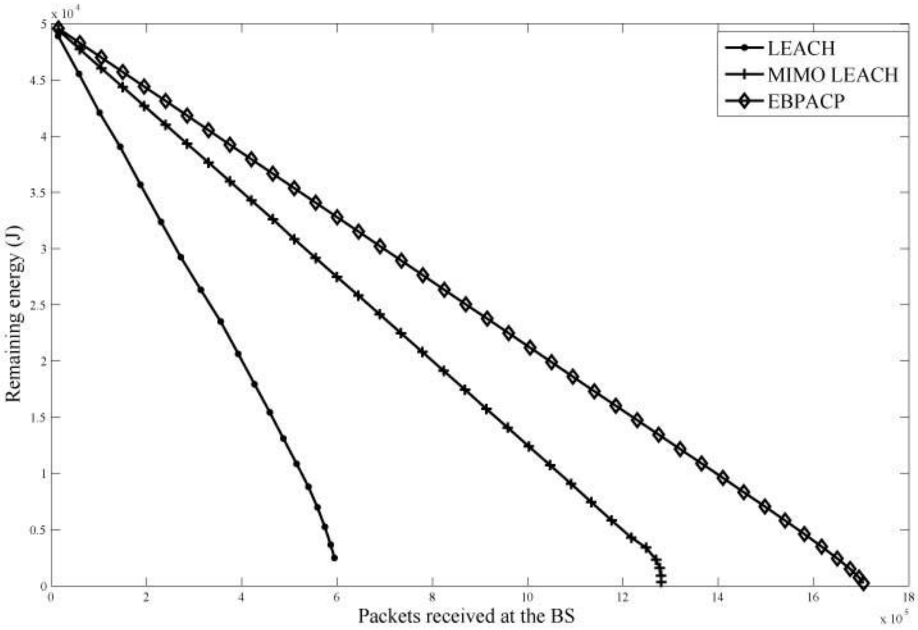

Fig. 8. Remaining energy vs packets arrived at the BS

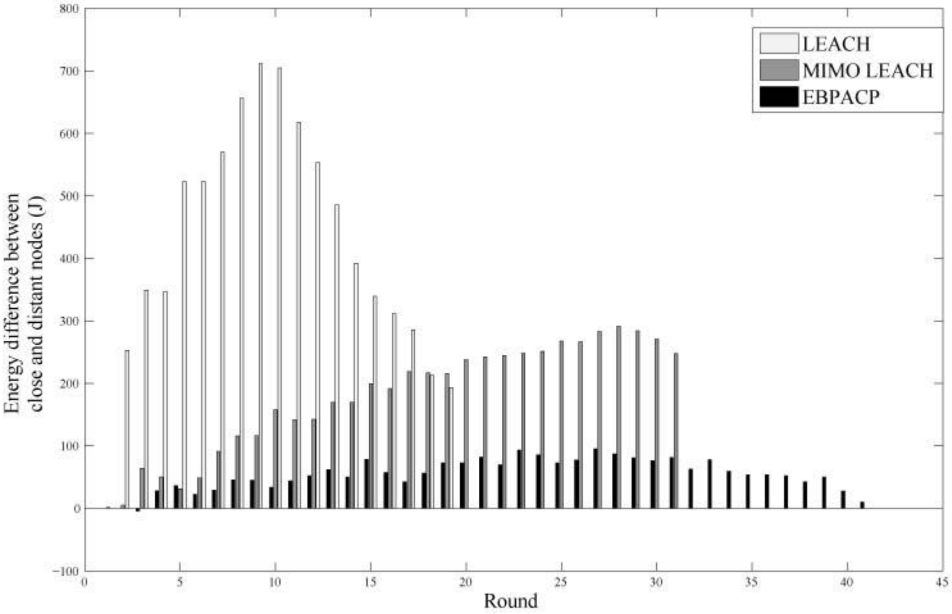

Fig. 9. Energy Difference Between Close and Distant Nodes

6. Conclusions

In our work, we first analyzed the impacts of system parameters and established a unified criterion to choose the proper cooperation scheme. This criterion serves as the basis of the proposed EBPACP to choose the number of cooperative nodes. In the design of EBPACP, energy balance is one of the main design goals. The key to balance energy is to adjust the cluster size and balance energy consumption between intra-cluster and inter-cluster. Sensor nodes require higher energy in inter-cluster communication are allocated smaller cluster size. Although for single-hop and multi-hop systems, sensor nodes have heavier burden of inter-cluster communication are different, the principle to balance energy remain unchanged. Our simulation is done based on single-hop and can be extended to multi-hop cluster-based WSNs as well.

In the future work, we will extend the simulation to multi-hop systems. Since latency is also an important research issue related to the performance of WSNs, we will analyze the latency performance of EBPACP in the future.

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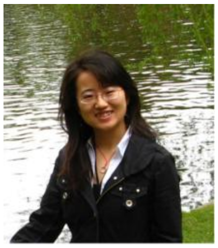

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