Basestation-Aided Coverage-Aware Energy-Efficient Routing Protocol for Wireless Sensor Networks

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***Abstract*—In wireless sensor networks, an energy-efficient routing protocol is a key design factor to prolong network lifetime. Recently, Optimal Coverage-Preserving Scheme (OCoPS) is proposed in [11] as an extension of the Low Energy Adaptive Clustering Hierarchy (LEACH) routing protocol with the coverage-preserving scheme which saves energy consumption through excluding redundant nodes of which sensing ranges are fully overlapped by their on-duty neighbors. In this paper, we propose a basestation-aided clustering-based routing protocol, namely, the Basestation-aided clustering routing protocol with the Coverage-Preserving Scheme (BCoPS). In BCoPS, the base station substitutes energy intensive tasks for deployed sensor nodes to prolong network lifetime. The performance of BCoPS is compared with the LEACH and OCoPS. The extensive simulation results show that BCoPS outperforms OCoPS by more than 20% on network lifetime and by more than 30% network lifetime until the coverage rate is higher than 80%.**

I. Introduction

Wireless sensor network (WSN) is a good candidate for applications such as battlefield surveillance, environmental monitoring, patients monitoring, and inventory managing [1][2][3]. In WSNs, one of the most significant constraints is the limited battery power of the nodes since the deployed nodes are infeasible to be recharged or be replaced once they are deployed in an unattended area. In this regard, it is worthwhile to pursue energy efficiency in WSNs. A large number of routing protocols have been proposed in the literature to achieve energy efficiency. Among the classified routing approaches such as data centric, location-based, and clustering [4] [5] [6], the clustering routing approach is well-known to be proper in the aspect of energy efficiency [7]. In clustering routing protocols, deployed nodes are divided into two groups in each cluster after cluster formation: one is a cluster head (CH), which performs data fusion and compression from gathered data and directly communicates with the base station (BS), and the others are non-cluster-head nodes, which perform sensing tasks and report the data to their CHs. Recently, in [6], Heinzelman et al. propose a distributed adaptive clustering routing protocol called the Low Energy Adaptive Clustering Hierarchy (LEACH), which employs random selection of CHs that perform most energy-intensive tasks among the nodes in a cluster. LEACH provides significant energy saving and prolongs network lifetime over other conventional protocols discussed in [6].

Heinzelman et al also propose a centralized version of LEACH (LEACH-C) in [8]. In LEACH-C, base station performs cluster formation instead of deployed sensor nodes while nodes configure themselves into clusters in LEACH. During the setup phase of LEACH-C, the base station receives information regarding the location and energy level of each node in a network. Using this information, the base station finds the optimal number of cluster heads and configures the network into clusters. Clusters are configured to minimize the energy required for non-cluster-head nodes to transmit their data to their CHs. Although the other operations of LEACH-C and LEACH are identical, results presented in [8] indicate a definite improvement over LEACH. The authors of [8] cite two key reasons for the improvement: configuration of better clusters and producing the optimal number of CHs. Since the base station utilizes its global knowledge of the network to produce better clusters that require less energy for data transmission. The number of cluster heads in each round of LEACH-C equals a predetermined optimal value, whereas for LEACH the number of cluster heads is randomly chosen from round to round.

Although LEACH and LEACH-C provides significant energy saving, due to dense deployment in WSNs, redundant nodes exist in the network, in which sensing ranges are fully overlapped by their on-duty neighbors. By excluding redundant nodes from on-duty mode for replacing dead nodes later without loosing the overall sensing coverage, as well as maintaining certain system reliability, another significant energy saving can be achieved [9]. Tian at al. [10] devise the Central Angle Calculation (CAC) scheme, which is a novel approach that calculates the central angle of nodes instead of the overlapped area to decide whether a sensor node can be turned off or not, and an extension of LEACH with the CAC scheme named the Coverage-Preserving Node Scheduling Scheme (C-PNSS). In the C-PNSS protocol, a global clock synchronization is required to solve the off-duty conflict problem, which generates coverage-holes when nodes make off-duty decisions simultaneously. To solve this problem, the random back-off scheme, which uses random time delay to make its off-duty decision, is used in C-PNSS. This scheme, however, does not guarantee no coverage-hole after turning some sensor nodes off. Boukerche at al. in [11] extend the CAC scheme to save more energy by the Extended Central

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Angle Calculation (ECAC) scheme and devise an extension of LEACH with the ECAC scheme named the Optimal Coverage-Preserving Scheme (OCoPS), which solves the off-duty conflict problem with the help of additional control messages. Since ECAC additionally considers another node of which distance from the coverage calculation target node is bigger than the sensing radius and smaller than twice of the sensing radius, more nodes can be turned off than using the CAC scheme. As a result, OCoPS with the ECAC scheme increases the network lifetime approximately 20% more than C-PNSS with the CAC scheme and guarantees no coverage-holes, but the extra energy consumption generated by using more control messages are not ignorable.

In this paper, we propose a basestation-aided clustering-based routing protocol with the coverage-preserving scheme named the Basestation-aided clustering routing protocol with the Coverage-Preserving Scheme (BCoPS) to save more energy. The key idea of BCoPS is that BS, which has a much faster processor and infinite energy source in the network, performs the energy-intensive setup tasks such as coverage calculation, wake-up strategy, cluster formation, creation of spreading code and time-division multiple access (TDMA) schedule instead of the deployed nodes. Simulation results show that BCoPS outperforms LEACH and OCoPS in network lifetime and network coverage rate. The rest of the paper is organized in the following form. We describe the coverage-preserving scheme basics in Section II. A detailed description of BCoPS is presented in Section III. We outline the network model and radio model for our simulation in Section IV. We provide performance evaluations of our protocol by the simulation results in Section V. Finally, we conclude this paper in Section VI.

II. Coverage-Preserving Scheme Basics

In general, the coverage-preserving scheme consists of the coverage calculation and wake-up strategy. In the first part of this section, we describe the coverage calculation. In the second part, we provide the required standards of the wake-up strategy that wakes eligible sleeping nodes up.

A. Coverage Calculation

The purpose of the coverage calculation is to find redundant nodes in which sensing ranges are fully overlapped or sponsored by their on-duty neighbors. CAC [10] is a novel scheme where off-duty nodes are calculated through the sponsored central angles of the nodes instead of overlaid areas. With using the angle antenna, such a scheme can resolve the coverage problem [10]. For example, tn Fig. 1(a), the overlaid area can be calculated as the shaded crescent area, the area can be calculated as the central angle, and the angle can be calculated by the equations below.

$$\theta_{j\to i} = 2\arccos\left(\frac{d(i,j)}{2r}\right) \quad (1)$$

where $\theta_{j\to i}$ denotes the sponsored angle of node j referred to node i, $d(i,j)$ denotes the distance from node i to node j, and r denotes the sensing radius of each sensor node [10].

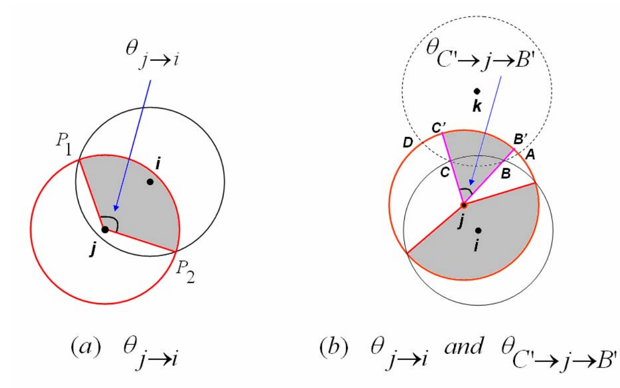

Fig. 1. Sponsored angle calculation - (a) CAC and (b) ECAC

$$\phi_{j\to i} = \arctan\left(\frac{Y_i - Y_j}{X_i - X_j}\right) \quad (2)$$

where $\phi_{j\to i}$ denotes the direction of node j referred to node i and X_i, Y_i, X_j, and Y_j denote coordinates for sensor i and j respectively [10].

Although the CAC scheme is useful in determining the crescent area as a central angle and its direction, it is also limited in that the CAC scheme only considers the cases where the distance between two nodes is less than or equal to the single sensing radius. As shown in Fig. 1(b), CAC scheme cannot calculate the upper shaded angle on node j by node i and k. As a result, more nodes in the network will be awake than necessary. To calculate the shaded angle, Boukerche et al. devise the ECAC scheme [11]. As made clear in the Fig. 1(b), the upper shaded angle can be calculated as follows. In the intersection point C of sensors i and k, the coordinates of sensor i and k are known, so, $\phi_{k\to i}$ and $\theta_{k\to i}$ can also be calculated by (1) and (2) respectively. Thus, the coordinates of C can be calculated as follows: $X_C = X_i + r * \cos(\phi_{k\to i} + \theta_{k\to i}/2)$ and $Y_C = Y_i + r * \sin(\phi_{k\to i} + \theta_{k\to i}/2)$. Coordinates of B can be calculated in the same way. After computing of B coordinates, we can calculate the sponsored angle $\theta_{C'\to j\to B'} = \arctan((Y_C - Y_j)/(X_C - X_j) - (Y_B - Y_j)/(X_B - X_j))$.

B. Wake-up Strategy

The wake-up strategy is one of the most important steps because it can influence both energy consumption and the quality of the monitoring task. As mentioned in [11], to devise a wake-up strategy, three standards are required. First, the sensing area of dead sensors should be replaced by the off-duty sensors as soon as possible to avoid coverage-holes. Second, the wake-up strategy should wake the necessary number of off-duty sensors up. Finally, the wake-up strategy should not consume the energy too much.

III. BCoPS

BCoPS is a basestation-aided clustering-based routing protocol with the coverage-preserving scheme for WSNs. As

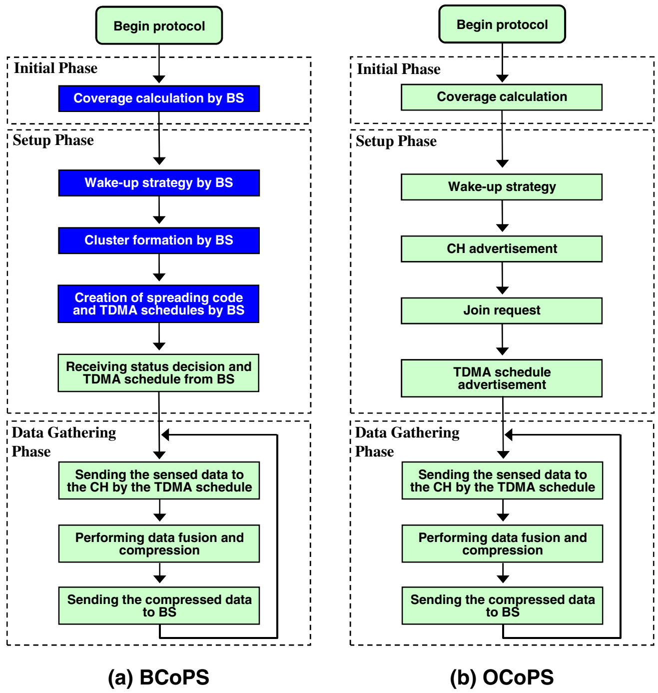

Fig. 2. Flow charts of the two routing protocols

shown in Fig. 2 in which flows colored in blue are performed by the BS itself, BCoPS consists of three major phases similar to the OCoPS protocol [11]: initial phase, setup phase, and data gathering phase. The initial phase is performed once at the beginning of the protocol and each round is composed of setup and data gathering phases successively. During a round, setup phase is run once at the beginning of each round and data gathering phase is run iteratively until the end of the round. In this section, we provide the detailed descriptions of these three phases.

A. Initial Phase

In the initial phase, the coverage calculation is performed. It calculates the sensing coverage to find redundant nodes in which the sensing ranges are entirely overlapped. In BCoPS, the BS computes the redundant nodes by using the ECAC scheme whereas for OCoPS deployed nodes compute the redundant nodes by message exchanges. As BS in BCoPS receives the location information of all deployed nodes at the beginning of the protocol, the BS performs the coverage calculation described in Section II by the BS itself and sends status decisions to all deployed nodes. As a result, deployed nodes in BCoPS do not need message exchanges to decide their status as well as do not need the extra control messages in order to guarantee a global clock synchronization because all coverage calculations are performed by the BS in a centralized manner.

B. Setup Phase

As can be seen in Fig. 2, in the setup phase two routing protocols perform the same activities with different manners. Like LEACH, in OCoPS, CHs are randomly selected and the CHs broadcast their status. The Non-CH nodes receive the status messages, choose their closest CHs, and send the join request messages to chosen CHs. Then, the CHs receive the messages, add them to their non-cluster-head node lists, create their TDMA schedules on the basis of the lists, and send their non-cluster-head nodes the schedules. Fig. 2 shows that BCoPS performs the setup phase with different manner. The detailed descriptions of the setup phase are below.

Step 1: The first major activity in the setup phase is the wake-up strategy. In BCoPS, we have two options for the wake-up strategy because the BS performs the wake-up strategy in a centralized manner. First, we can easily decide the eligible wake-up nodes from the cross points, where the target area is divided into $1m \times 1m$. In this strategy, each cross point checks whether it is in the sensing radius of at least one on-duty node. If there is no on-duty node within the distance, one of off-duty nodes within the sensing radius should be waked up. This strategy, however, is easy to implement but computational complexity is too high. Second, when an on-duty node is reported as a dead node, the BS performs the coverage calculation reversely. Thus, by subtracting the overlapped or sponsored angles, which were obtained from the dead node during the coverage calculation, we can wake eligible off-duty nodes, where all angles are not entirely sponsored by their on-duty neighbors after subtracting the sponsored angles of the dead node. In our simulation, we implement the second alternative in order to relieve the BS of the computational burden. After the wake-up strategy, the BS sends the wake-up messages to the prospective on-duty nodes at the beginning of every round because off-duty nodes can receive the message only in this time.

Step 2: The second major activity in the setup phase is the cluster setup. In BCoPS, the balanced clustering technique proposed in [12] is used for cluster formation. A single iteration of the cluster splitting algorithm performed by BS itself consists of the following four procedures;

- Procedure 1: From the set S which contains all nodes that are eligible to become CHs, choose two nodes, N_1 and N_2, that have the maximum distance in the deployed area.
- Procedure 2: Group each of the remaining nodes in the current cluster with either N_1 or N_2, whichever is closest.
- Procedure 3: Balance the two groups so that they have approximately the same number of nodes. As a result, this forms the two sub-clusters.
- Procedure 4: Split the set S into smaller sets s_1 and s_2 according to the sub-cluster groupings performed in procedure 3.

The BS repeats this iteration until the desired number of CHs is attained. The resulting sub-clusters have approximately the same number of sensor nodes and the distances in each sub-cluster members are also minimized.

Step 3: The creation of the spreading code and TDMA schedule is the last major step in the setup phase. BCoPS utilizes code-division multiple access (CDMA) to deal with the inter-cluster interferences and TDMA to deal with intra-cluster collisions. After cluster formation, the BS assigns C_ID to all on-duty nodes in order to deal with inter-cluster interferences and T_ID to all non-cluster-head nodes in each cluster in order to deal with collisions among the non-cluster-head nodes. In the creation of the spreading code and TDMA schedule, when the number of the spreading codes is C and the number of non-cluster-head nodes is M, we assign first $\log_2 C$ bits for the C_ID and the next $\log_2 M$ bits for the T_ID, which represent the identification numbers of the CDMA and TDMA for a node respectively. For instance, the C_ID is 5 (101) out of 8 for the cluster which has 4 non-cluster-head nodes, the C_ID and T_ID of the 4 nodes will be 10100, 10101, 10110, 10111 respectively. When 10100 is assigned to the CH, nodes with 10101, 10110, and 10111 transmit their data in time slots 1, 2, and 3, respectively. When 10101 is assigned to the CH, nodes with 10100, 10110, and 10111 transmit their data in time slots 1, 2, and 3, respectively. This rotation of T_ID for the CH is performed until the end of the round. Finally, after performing these three steps, the BS sends status decisions to all alive nodes and schedules of the spreading code and TDMA to all on-duty nodes at the beginning of every round. In BCoPS, receiving these messages is what all deployed nodes should do in the setup phase.

C. Data Gathering Phase

As shown Fig. 2, all operations in this phase between two routing protocol are the same but consumed energy is saved in BCoPS. Since BCoPS uses the balanced clustering technique, sensor nodes are grouped into clusters in which all non-cluster-head nodes contain the smaller spatial separations than OCoPS. Thus, the transmissions consume minimal energy due to the smaller spatial separations between a CH and the non-cluster-head nodes in each cluster. After each CH receives the data from all its non-cluster-head nodes in a cluster, the CH performs data fusion on the collected data, and compresses the data. The CH finally sends the compressed data to the BS with its spreading code to deal with the inter-cluster interference.

IV. Network Model and Radio Model

In this section, we provide our simulation environments. In the first part of this section, we describe the network model. The second part presents the radio model.

A. Network Model

We assume the same network model used in [6][11]. A fixed BS is located far away from the sensor nodes. All sensor nodes in the network are immobile, homogeneous, and deployed in a flat area (2-dimension). In addition, all sensor nodes always have data to transmit, sense the environment at the constant rate, and can directly communicate with the fixed BS. Each node controls power so that it expends the minimum required energy to transmit data to its destination.

B. Radio Model

We assume the same model used in [6][11]. In a transmitter and receiver, radio expands energy for transferring and receiving k-bit with the distance of d meter is given in (3) and (4) respectively.

$$E_{T_x}(k,d) = E_{T_x}k + E_{amp}(k,d) \tag{3}$$

where $E_{T_x}(k,d)$ denotes the total energy dissipated at the transmitter with k bits and d distance, E_{T_x} denotes per bit energy dissipations for transmission, and $E_{amp}(d)$ denotes the energy required by the amplifier for an acceptable signal-to-noise ratio.

$$E_{R_x}(k) = E_{R_x}k \tag{4}$$

where $E_{R_x}k$ denotes the energy dissipated at the receiver and E_{R_x} denotes per bit energy dissipations for reception. We use both the free-space propagation model and the two-ray ground propagation model for the path loss in wireless channel transmission. With d_o which denotes the threshold of transmission distance, the free-space model is employed where $d \leq d_o$ and the two-ray model is employed where $d > d_o$. $E_{amp}(d)$ which denotes required energy by an amplifier is defined as

$$E_{amp}(d) = \begin{cases} \varepsilon_{FS} * d^2, & d \leq d_o \\ \varepsilon_{TR} * d^4, & d > d_o \end{cases} \tag{5}$$

where ε_{FS} and ε_{TR} denote amplifier parameters for the free-space and the two-ray models, respectively, and d_o is the threshold distance given by

$$d_o = \sqrt{\varepsilon_{FS}/\varepsilon_{TR}} \tag{6}$$

We assume the same parameters used in [11] for our simulation: $E_{T_x} = E_{R_x} = 50nJ/bit$, ε_{FS} $=10pJ/b/m^2$, $\varepsilon_{T_x} = 0.0013pJ/b/m^4$, $d_o = 87m$, and the energy cost for data aggregation is set as $E_{DA} = 5nJ/b/message$. Other detailed simulation parameters will be provided in Section V.

V. Performance Evaluation

In this section, we define the network lifetime, coverage rate, and coverage redundancy. We also present simulation results performed on Network Simulator NS-2 [13] concerning the alive nodes, on-duty nodes, network coverage rate, and coverage redundancy. The purpose of this simulation is to confirm the improvement of network lifetime and network coverage rate at the expense of network coverage redundancy and the heavier burden of the BS. For the comparison, we simulate the BCoPS, LEACH, and OCoPS routing protocols. In the simulation, we assume the same scenario used in the OCoPS routing protocol [6] [11]. 100 nodes are uniformly distributed in $50m \times 50m$ area. Each sensor has initial energy of 2J and the sensing range of 10 meters and knows its geographical location. Each sensor sends 2000-bit message to BS. Finally, for the coverage calculation, the target area is divided into $1m \times 1m$ and the $2601(51 \times 51)$ cross points detect whether they are in the sensing range of on-duty nodes every 0.5 second.

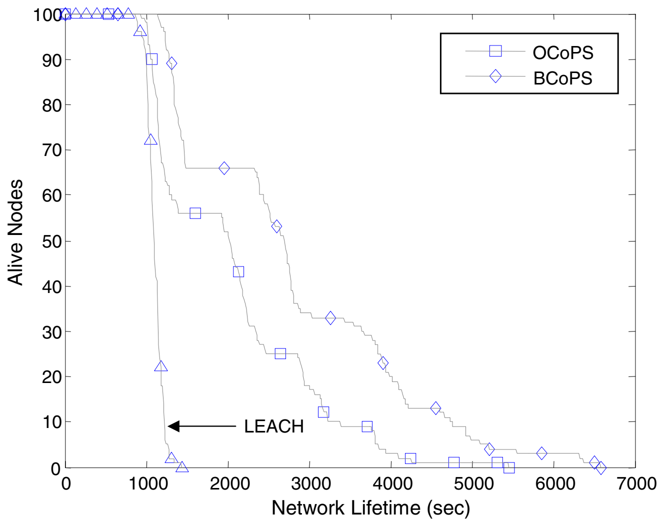

Fig. 3. Alive nodes as the network lifetime function

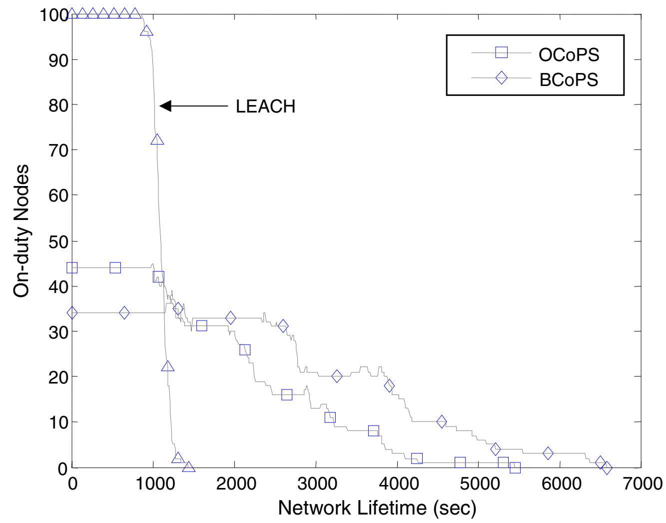

Fig. 4. On-duty nodes as the network lifetime function

A. Alive Nodes as Network Lifetime Function

Fig. 3 shows alive nodes as the network lifetime function of three routing protocols, namely LEACH, OCoPS, and BCoPS. We define network lifetime as the overall time range during which at least a sensor node in a network has the ability to monitor its environment [11]. Our simulation result shows that the network lifetime of LEACH is 1450, that of OCoPS is 5400, and that of BCoPS is 6500. The BCoPS protocol increases network lifetime nearly 20% more than OCoPS and nearly 5 times more than LEACH. The main factor of the network lifetime increment is that, in BCoPS, the BS substitutes energy intensive tasks such as coverage calculation, wake-up strategy, cluster formation, and creation of spreading code and TDMA schedule for deployed sensor nodes to prolong network lifetime. The balanced clustering technique additionally increase the network lifetime by minimizing the communication distance among the non-cluster-head nodes in each cluster.

B. On-duty Nodes as Network Lifetime Function

Fig. 4 shows on-duty nodes as the network lifetime function of the three routing protocols. This figure also shows the network lifetime increment from another viewpoint. There are two noteworthy points. First, the number of on-duty nodes among the three routing protocols is different. It is because LEACH performs routing without using the coverage-preserving scheme. BCoPS utilize the BS for initial and setup phases,whereas deployed nodes performs the same tasks in OCoPS. Second, the curves of both BCoPS and OCoPS, visible in Fig. 4, are shaped approximately like steps. There are two reasons for this: cluster heads (CHs) random selection used in LEACH and the off-duty replacement by the wake-up strategy [11]. Since both routing protocols are extensions of the LEACH protocol and use the random selection of CH like the LEACH protocol [6], each on-duty node has the same chance to be a CH. In LEACH, the network has a steady phase and by the load balancing, nodes start to die simultaneously after a certain time. By coverage-preserving scheme and wake-up strategy, BCoPS and OCoPS replace dead nodes with off-duty nodes. After all the dead nodes are replaced, both have another steady phase. This replacement and steady phase cycle is repeated until there are no replaceable nodes. Fig. 3 also shows the dead node replacements from another point of view.

C. Network Coverage Rate as Network Lifetime Function

Fig. 5 shows the network coverage rate of three protocols. We define coverage rate as what percentile of target area (50×50) is covered by on-duty nodes. The purpose of calculating the network coverage rate is to check how much percentage of our target area ($50m \times 50m$) is covered by on-duty nodes as the lifetime function. The initial coverage rate is used as the base value (100%). The network coverage rate of the BCoPS protocol is compared with the LEACH and the OCoPS protocols, which is LEACH extension with the coverage-preserving scheme. As shown in Fig. 5, in the BCoPS protocol, the network coverage rate drops to 80% approximately at 3870 seconds while LEACH is at 1150 seconds and OCoPS is at 2980 seconds. These results show our routing protocol outperforms by nearly 30% and 3.3 times on network lifetime until the network coverage rate is higher than 80%.

D. Coverage Redundancy as Network Lifetime Function

Fig. 6 shows the coverage redundancy as the network lifetime function of the three routing protocols. We define coverage redundancy as the summation of the number of on-duty nodes for each cross point in which the target area is divided into $1m \times 1m$ grids. The purpose of this simulation is to show the trade-off between the improvement of the network lifetime and the decrement of network coverage redundancy. As can be seen, LEACH has a significantly large number of redundancies at the beginning and decreases near 1000 seconds sharply while other two routing protocols are not

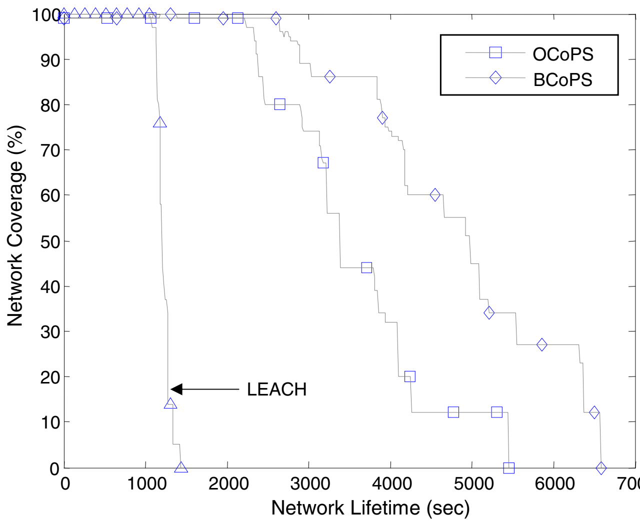

Fig. 5. Network coverage rate as the network lifetime function

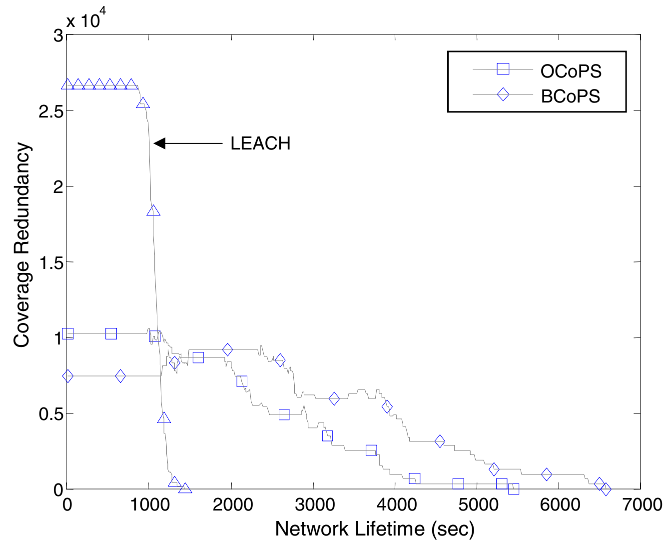

Fig. 6. Coverage redundancy rate as the network lifetime function

that much. Especially, in the BCoPS protocol, the coverage redundancy increases approximately to 1100 seconds. It is because the dead node replacements by off-duty nodes wake more nodes up than the coverage calculation while OCoPS does not have enough nodes to wake up. As a result, as shown in Fig 5, the insufficient number of on-duty nodes causes the decrement of the network coverage rate of the OCoPS routing protocol.

VI. Conclusion

In this paper, we propose a Basestation-aided clustering-based routing protocol with the Coverage-Preserving Scheme named the BCoPS. In BCoPS, the BS, which has a much faster processor and infinite energy source in the network, substitutes energy intensive initial and setup tasks such as sensing coverage calculation, wake-up strategy, cluster formation, and creation of the spreading code and TDMA schedule for the deployed sensor nodes. Additionally, the well-balanced cluster formation guarantees the adequate number of clusters and the smaller communication distance among the non-cluster-head nodes than the LEACH and OCoPS routing protocols during data gathering. Extensive simulations show that the BCoPS protocol outperforms the LEACH and OCoPS protocols over network lifetime and network coverage rate. For future work, it is required to extend the BCoPS protocol to a multi-hop routing protocol for another energy saving.

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