WSN Lifetime Elongation via Hybrid Routing

Amr Y. Mostafa†, Samy S. Soliman‡, Nada El-Gaml‡, Ramez M. Daoud†,
Hassanein H. Amer†, Ahmed Khattab‡
† ECNG, American University in Cairo, Egypt
‡ EECE, Cairo University, Egypt
amryoussef@aucegypt.edu, samy.soliman@cu.edu.eg, {rdaoud, hamer}@aucegypt.edu, akhattab@ieee.org

***Abstract*—Wireless sensor networks is one of the most promising elements of the Internet-of-Things. Faced with many challenges, energy dissipation and lifetime are among the main performance metrics that require improvement. In this paper, a new hybrid routing protocol is proposed to elongate the lifetime of a sensor network. The proposed hybrid protocol overcomes the LEACH-C shortcomings and exploits the advantages of direct transmission. The proposed protocol is tested, through simulation, on various network sizes and various numbers of sensors. It is shown that the proposed hybrid protocol provides lifetime improvement over both LEACH-C and direct transmission. It is shown also that such improvement depends on the network parameters, namely the size and the number of sensors. Hence, scenarios where the hybrid protocol provides significant improvement are distinguished from those where it provides modest improvements.**

***Index Terms*—Direct transmission; Internet-of-things; hybrid routing; LEACH-C; lifetime; wireless sensor networks.**

I. Introduction

Wireless sensor networks (WSNs) have attracted the interests of both academia and industry for decades. Such interest has been increasing because of the unprecedented advances in digital electronics, and wireless communications. As a result, WSNs currently have a wide range of applications including environmental monitoring, security surveillance, military applications and others. A WSN is composed of large numbers of sensor nodes with relatively limited energy storage, as well as limited processing and communications capabilities. Sensor nodes are responsible for gathering, processing and transmitting data to an end observer. More recently, with the evolution of the Internet-of-Things (IoT), the world is ambitious to have networks that are capable of capturing every piece of information of the surroundings [1]. This means that low-power sensor nodes should be capable of collecting, analyzing and transmitting huge amounts of data to an IoT cloud. Energy dissipation is one of the major challenges of WSNs. Usually, sensor nodes are pre-equipped with low-power batteries which cannot be easily replaced, mostly because of the inaccessibility of the sensors [2]. It is required though to make best use of the network and maximize its lifetime. For this reason, many researchers have proposed energy efficient strategies to improve the lifetime of WSNs [3–11].

One of the pioneering works on energy-efficient strategies is LEACH [3] and its centralized version, LEACH-C [4]. In LEACH-C, the network is divided into clusters. For each cluster one sensor is selected as a cluster head (CH). Only the CH is responsible for transmitting data to a base-station (BS), sometimes referred to as a sink node, after receiving data packets from the cluster members. The formation of clusters is updated each round with all overhead calculations performed at the BS. At the beginning of each round, each node sends a packet with its location as well as the residual energy to the BS. Accordingly, the BS chooses nodes that have residual energies higher than the average energy of all nodes in order to be eligible for being CHs. Simulated annealing algorithm [4] is then performed in order to select the optimum CHs from the eligible nodes. Once the BS decides on the CHs and their associated cluster members, it broadcasts a message to all nodes with CHs identifications, and clusters are formed [4].

As a hierarchical routing protocol, LEACH-C has many advantageous features. One of such features is the even distribution of energy dissipation among all nodes. Another feature is the minimization of the transmission distances in the network especially for nodes that work as cluster members during its round. As a result of these features, LEACH-C minimizes the energy consumption in the network, hence maximizes the lifetime. The lifetime improvement achieved by LEACH-C mainly appears in networks where the BS is located a long distance from the main network [4]. Many attempts to modify LEACH-C to improve its performance exist in the literature, cf. [10, 11] and references therein.

In this paper, we focus on sensor networks where the BS is located within the vicinity of the sensor nodes. For such networks, we propose a hybrid routing protocol that partially uses LEACH-C where advantageous, and partially uses direct transmission where LEACH-C shows no advantage. The proposed hybrid protocol is introduced in Section II. Simulation results of the proposed protocol are also presented in Section II for a network example that is most common in the literature. In Section III, the performance of the proposed protocol is tested on various network structures. Finally, the paper is concluded in Section IV.

II. Hybrid Routing Protocol

In this section, we propose a hybrid protocol that combines the advantages of the LEACH-C protocol and those of direct transmission in order to 1) maximize the network's lifetime and to 2) alleviate the shortcomings of LEACH-C. Among the disadvantages of LEACH-C is the overhead calculations at the BS and the data aggregation at the CHs. This can lead to transmission delays, for which some WSN applications

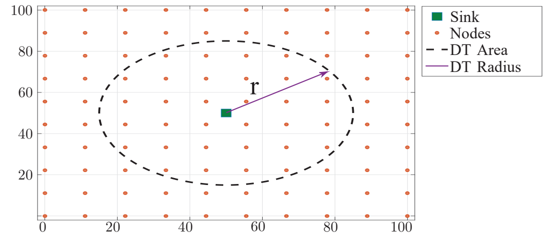

Fig. 1. Network example of $100m \times 100m$ with 100 nodes.

are sensitive, e.g. factory automation WSNs or emergency-reporting WSNs. Moreover, in LEACH-C, a CH failure will result in all nodes within the cluster are not able to send their data to the BS. Finally, although LEACH-C was an enhancement on the LEACH protocol that improved the load balancing, the pre-selection of a CH leads to unbalanced distribution of energy consumption since nodes that are chosen as CHs dissipate more energy than other nodes [3, 12].

While the CH, in LEACH-C, is responsible for collecting data from the sensor nodes, in direct transmission, all nodes can send their data directly to the BS. Therefore, the bigger the network and the distances between nodes and the BS, the more energy consumption is needed in the network. This makes direct transmission undesirable for large networks. However, in relatively small networks, where nodes are relatively close to the BS, direct transmission can be a better option than LEACH-C from the perspective of energy saving and lifetime elongation. Direct transmission has two more advantages over LEACH-C. Since all nodes transmit their data directly to the BS, data delivery occurs in real-time with no overhead calculations at the BS or at any transmitting node. Additionally, in the case of any node failure, only such node fails to send its data to the BS while all the other nodes remain unaffected and can transmit their data to the BS.

A. The Proposed Hybrid Protocol

For the proposed hybrid protocol, the sensor nodes are categorized into two categories, each applying one of two different routing protocols. Nodes that lie within a specific, predefined distance from the BS will transmit their data directly to the BS, while other nodes beyond this distance will transmit their data using the LEACH-C protocol. This categorization is based on the assumption that the BS is within the transmission range of sensor nodes using direct transmission. It is also assumed that the underlying Layer-2 protocol resolves issues resulting from interference. Figure 1 shows the traditional $100m \times 100m$ network example, where 100 sensor nodes are uniformly distributed over an area of $100m \times 100m$. It is assumed that the BS is located at the center of the network. Hence, sensor nodes within a radius, r, will transmit directly to the BS, while nodes outside such radius will follow LEACH-C protocol.

B. Energy Calculations

In this subsection, we present the used energy dissipation model for each round. For sensor nodes that use direct transmission, the energy dissipated, $E_T(k_n, d)$, to transmit data directly to the BS is a function of both the transmission distance, d, and the number of bits per message, k_n [2, 4]

$$E_T(k_n, d) = k_n\ E_{\text{elec}} + k_n\ E_{\text{amp}}(d) \tag{1}$$

where E_{elec} is the energy dissipated per bit to transmit or receive data, and $E_{\text{amp}}(d)$ is the energy required to maintain a tolerable signal to noise ratio along the transmission distance, d. Using the same signal propagation model used in [4],

$$E_{\text{amp}}(d) = \begin{cases} \epsilon_{\text{fs}}\ d^2, & d \leq d_0 \\ \epsilon_{\text{amp}}\ d^4, & d > d_0 \end{cases} \quad \text{where, } d_0 = \sqrt{\frac{\epsilon_{\text{fs}}}{\epsilon_{\text{amp}}}} \tag{2}$$

where ϵ_{fs} and ϵ_{amp} are the amplifier energies when $d \leq d_0$, and $d > d_0$, respectively. For sensor nodes beyond a distance r from the BS, the LEACH-C protocol is used. Hence, the energy, $E_{\text{non-CH}}$, dissipated by a non-CH node at a distance d_i from its CH is calculated as [4]

$$E_{\text{non-CH}}(k_n, d_i) = k_n\ E_{\text{elec}} + k_n\ E_{\text{amp}}(d_i). \tag{3}$$

Assuming N_c is the number of non-CHs in a cluster, E_{agg} is the data aggregation energy and k_c is the aggregated data size, the total energy dissipated by a CH, $E_{\text{CH}}(k_n, k_c, d_i)$, is given as [4]

$$E_{\text{CH}}(k_n, k_c, d_i) = k_n N_c E_{\text{elec}} + k_n E_{\text{agg}} + k_c E_{\text{elec}} + k_c E_{\text{amp}}(d_i). \tag{4}$$

It is conjectured that the energy dissipation of a group of nodes at a relatively small distance from the BS is less in direct transmission than in LEACH-C. On the other hand, a group of nodes will dissipate less energy as a cluster using LEACH-C if they are at a relatively large distance from the BS. This will be shown in the following section.

Note that the direct transmission radius, r, can be arbitrarily chosen. However, it is expected that the network's lifetime will be dependent on such parameter. Consequently, the direct transmission radius can be optimally selected to improve the network's lifetime over those obtained through LEACH-C only or direct transmission only. This will be experimentally shown in the following subsections.

It should be also noted that the parameter r can be varied dynamically throughout the operation of the network in order to reflect the variations of the sensor-BS links from one sensor to another and from one time to another. However, in this work, we adopt the common assumption that the link variation is resulting from the power propagation loss [3–12]. Hence, r is a predefined parameter that does not need variation with respect to the network's sensor nodes. Consequently, no additional overhead cost is incurred and lifetime improvement is cost-free.

C. Experiment Setup

MATLAB is used to simulate the network's operation. The network parameter values are obtained from [13]. The initial energy for all sensor nodes is assumed 1J. The optimum number of CHs for the network is chosen using the same optimization process in LEACH-C [4].

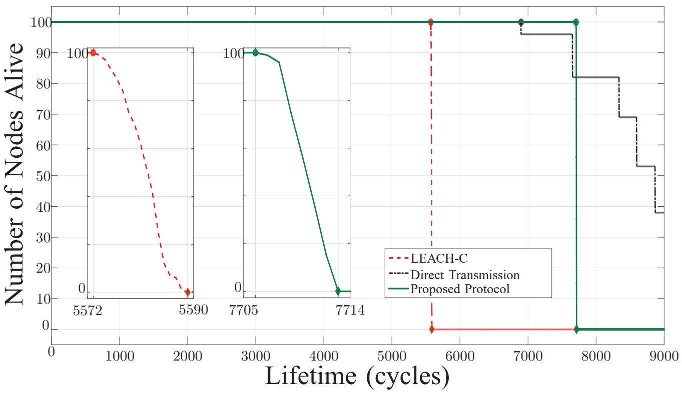

Fig. 2. Lifetime performance for a $100m \times 100m$ network with 100 nodes.

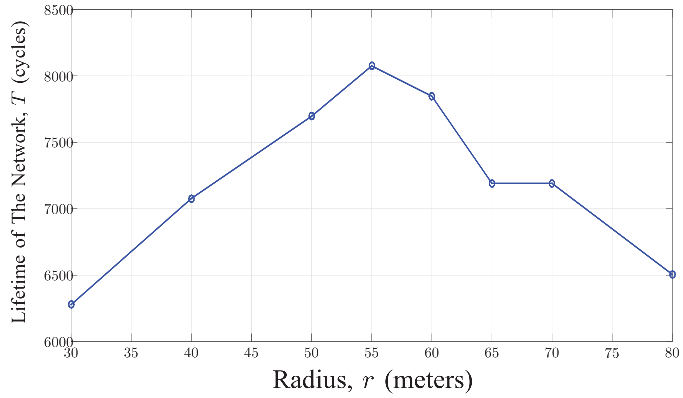

Fig. 3. Network's lifetime as a function of the direct transmission radius, r.

D. Results and Analysis

Figure 2 shows the total number of nodes that remain alive for the $100m \times 100m$ network example. The results are shown for the cases of using direct transmission only, using LEACH-C only, and using the proposed hybrid protocol, where the direct transmission radius is chosen as $50m$. It can be seen from Fig. 2 that LEACH-C has worse performance than direct transmission in terms of lifetime[1]. This result can be expected because the BS is close to the sensor nodes. More importantly, it can be seen that the proposed hybrid protocol results in a better lifetime than both LEACH-C alone and direct transmission alone. In this network example, the lifetime, achieved by using the proposed hybrid protocol, is improved by 12% compared to direct transmission, and 38.4% compared to LEACH-C.

As mentioned earlier, the selection of the direct transmission radius, r, has an effect on the network's lifetime. In order to study such effect, various values of such radius are used to evaluate the network's lifetime. Note that the variation of such radius will not only affect the number of the sensor nodes that will transmit their data directly to the BS, but also it will affect the optimum number of CHs, and consequently, the LEACH-C clusters. Figure 3 shows the lifetime of the network when the proposed hybrid routing protocol is used for various values of the direct transmission radius. It can be seen that the network's lifetime is peaked when the direct transmission radius is set to $55m$. This means that about 80% of the nodes are using direct transmission. However, it will be shown in the next section that for bigger networks, the optimum radius varies, and consequently the percentage of nodes that use the direct transmission protocol varies.

III. Performance of the Protocol on Bigger Networks

In this section, we explore the performance of the proposed hybrid protocol in the cases of bigger networks where the number of sensor nodes span larger areas.

[1]Note that in defining the lifetime here, we adopt the definition of the first node death. This definition is often used for applications that require full coverage of the network with active/alive sensor nodes.

In the first example, we study a $150m \times 150m$ network with 225 sensor nodes. This represents the same sensor density as that of the $100m \times 100m$ network example. The BS is still assumed at the center of the network. Other network parameters are still the same as the previous section.

It is found that the lifetime is maximized at a radius of $75m$. With this radius used, Fig. 4 shows the network performance, in terms of the nodes remaining alive, for the proposed hybrid protocol as well as for LEACH-C and direct transmission protocols. It can be seen that the lifetime resulting from the hybrid protocol is 89% higher than that resulting from direct transmission, and 16% higher than that resulting from LEACH-C. Recall that these lifetimes are evaluated as the number of cycles to the first node death.

It is noteworthy to mention that the lifetime resulting from direct transmission, in this case, is less than that resulting from LEACH-C, as opposed to the case of the $100m \times 100m$ network in Fig. 2. This is expected because in larger networks, the distances between the BS and the sensor nodes are larger. In such cases, the advantages of LEACH-C over direct transmission are evident. On the other hand, the use of the proposed hybrid protocol allows the nodes that are close to the BS to send their data directly, while farther nodes use the dual-hop LEACH-C protocol to send their data to the BS. This is the reason of lifetime elongation achieved by the hybrid protocol.

Figure 4 shows also the 75% lifetime [2] which is defined as the number of cycles where at least 75% of the sensor nodes are still active. It can be noticed that the 75% lifetime of the network following the hybrid protocol is still superior to that obtained from other traditional protocols.

It can be also seen from Fig. 4 that, in the case of direct transmission, the sensor nodes become inactive gradually. This is expected because the sensor nodes at large distances from the BS will require higher amounts of energy for their direct transmission and hence deplete their energies quickly, while nodes close to the BS can sustain more direct transmissions. For example, direct transmission requires 3209 cycles (from cycle 3214 to cycle 6423) so that all sensor deplete their energies. On the other hand, LEACH-C allows even distribution of energy dissipation, as mentioned earlier, and hence the sensors

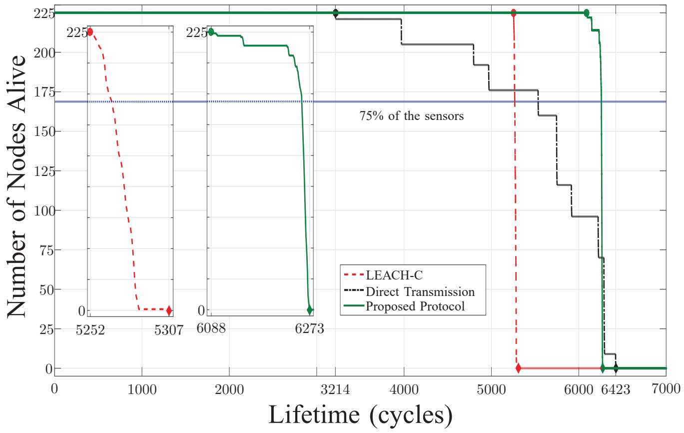

Fig. 4. Lifetime performance for a $150m \times 150m$ network with 225 nodes

deplete their energies at consecutive cycles.

For example, it can be seen from Fig. 4 that while the first node dies at cycle number 5252, the last node dies at cycle number 5307. For the proposed hybrid protocol, the rate of sensors' death is in between those of direct transmission and LEACH-C. For example, the 100 sensor nodes die within 185 cycles (from cycle 6088 to cycle 6273). This emphasizes the advantage of the proposed hybrid protocol that it can sustain node deaths for a longer number of cycles.

It can be noticed from the previous examples that the bigger the network, the less the improvement of the proposed protocol over LEACH-C. However, the advantages of the proposed protocol are not limited to lifetime elongation. The proposed protocol is advantageous in time-sensitive applications because nodes which transmit directly to the BS require one transmission hop to send their data. This is not the case for LEACH-C. Additionally, the proposed protocol has the advantage of failure immunity because a considerable number of sensors send data directly to the BS. Hence, there is a lower probability that the BS will not receive sensed data.

In the following, we verify our previously mentioned assumption, that the energy dissipated by a cluster at a relatively short distance from the BS is more using LEACH-C protocol, for a $200m \times 200m$ network. A cluster was randomly chosen within 50 meters from the BS. The energy dissipated by this cluster, using LEACH-C protocol, added up to 0.0033J, while the energy dissipated using direct transmission is 0.002J. On the other hand, for a cluster that is far from the BS, the energy dissipated by all the cluster members during one round using LEACH-C was 0.0037J, while the same cluster dissipates 0.0049J using direct transmission. This supports the proposed protocol, which uses direct transmission with nodes in a short distance from the BS, and LEACH-C with nodes that lie beyond a certain distance from the BS. It is also worth noting that the energy dissipated using LEACH-C does not change significantly when a cluster's position is changed. The reason behind this is that most of energy dissipated in the cluster is due to transmitting and receiving data between the cluster members and the CH, which is constant regardless of the position of the cluster. The only difference is the distance over which the CH sends the collected data to the BS, which causes minor changes in the overall energy dissipation.

IV. Conclusion

In this paper, a hybrid routing protocol has been proposed for wireless sensor networks where the sink node is located in the close vicinity of the sensors. Sensors surrounding the sink node, i.e. within a specific distance, r, from the sink, send their data directly to the sink node, while the remaining sensors are clustered similar to LEACH-C. It was shown that the proposed protocol results in network lifetimes that exceed those resulting from direct transmission only or from LEACH-C only. It was observed that the improvement percentage varies according to the network size and the number of sensors. It was shown also that the network's lifetime is dependent on the radius, r, and hence can be further improved by selecting the parameter r optimally.

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