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A Cooperative Learning Scheme for Energy Efficient Routing in Wireless Sensor Networks

Sami S. Alwakeel
Computer Engineering Department
King Saud University
Riyadh, Saudi Arabia
Affiliated Researcher ; Sensor Network & Cellular System Center , Tabuk University , Saudi Arabia
swakeel@ksu.edu.sa

Najla A. Al-Nabhan
Computer Science Department
King Saud University
Riyadh, Saudi Arabia
Affiliated Researcher ; Sensor Network & Cellular System Center , Tabuk University, Saudi Arabia
nalnabhan@ksu.edu.sa

***Abstract*— Wireless sensor networks (WSNs) are gaining more interest in variety of applications. Of their different characteristics and challenges, network lifetime and efficiency are the most considered issues in WSN-based systems. The scarcest WSN's resource is energy, and one of the most energy-expensive operations is route discovery and data transmission. This paper presents a novel design of a cooperative nodes learning scheme for cooperative energy-efficient routing (CEERA) in wireless sensor networks. In CEERA, nodes perform a cooperative learning in delivering data to the base station. The retransmission of packets is controlled through an address-based timer. CEERA achieves overhead reduction and energy conservation by controlling various parameters that affect the overall network efficiency. Performance results are evaluated using NS2 simulator and our own implemented event-driven simulation. The simulation results show that our algorithm minimizes the overall energy consumption of the WSN, extends network operational lifetime, and improves network efficiency and throughput.**

Keywords-Wireless Sensor Networks; Energy Efficient Routing Algorithms; Cooperative Learning; Cooperative WSN Routing Algorithms.

I. Introduction

Wireless Sensor Networks (WSNs) are of great importance. They are increasingly became attractive means to provide more advanced, intelligent, and context-aware systems with implicit user interaction. A WSN consists of a large number of cooperating small-scale nodes with sensing, limited computation, and wireless communication capabilities. In various applications including geophysical monitoring, precision agriculture, habitat monitoring, transportation, health, military systems and business processes, WSNs are envisioned to be used to fulfill complex monitoring tasks. With this new class of networks also come new challenges in many areas of the system's design.

WSNs pose their unique challenges due to the lack of central entity for organization, sensors limitation, mobility of participants and limited range of wireless communications. Moreover, in most of WSN applications, sensors are deployed flexibly and quickly with minimal effort eliminating the need for physical infrastructure.

In WSNs, a sensor node typically includes: a sensing unit to sense the environmental parameter, a microcontroller to execute local data processing (such as video compression and routing algorithms), a radio transceiver to send/receive sensed and/or control data through a wireless medium. The entire sensor is powered by battery or other power source (i.e. solar energy) with a lifetime of several months to a few years [1].

The sensing units are continuously detecting events and may communicate the collected information to the BS according to some predetermined parameters characterizing the collected data. Communication among nodes is usually done, as shown in Fig. 1, in a cooperative multi-hop fashion until reaching the base station.

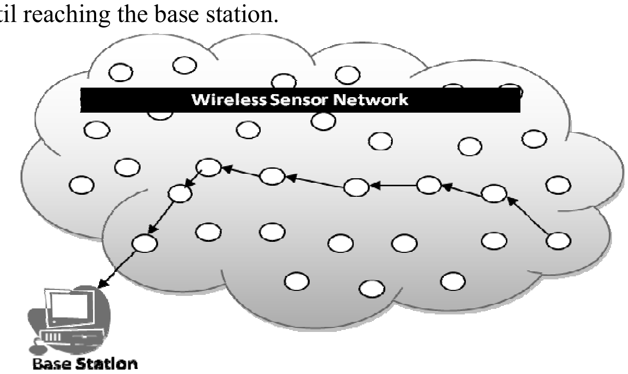

Fig. 1. Architecture of WSN.

The scarcest WSN's resource is energy. When a sensor node decides to initiate a transmission to a certain destination terminal, a routing operation is necessary to find a route from the source to the destination. Unfortunately, data transmission and route discovery are considered of the most energy-expensive operations. As sensor nodes are severely constrained by the amount of battery power available, it is necessary for any WSN communication protocol to conserve nodes' energy to maximize their lifetime. The random node deployment, untended nature of sensor nodes, hazardous sensing environment that precludes manual battery replacement all together necessitates the design energy efficient algorithms for WSNs. Algorithmic researches in WSN are generally focus on the study and design of energy-aware algorithms. Various techniques were developed in the literature to tackle this problem. However, most of the existing routing algorithms are based on these energy-expensive operations [1-19].

This paper presents a novel design for a cooperative energy-efficient routing algorithm (CEERA) for wireless sensor network. In CEERA, nodes cooperate in delivering

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data to the base station. Our algorithm efficiently avoids the above described consumption in energy as it does not require any prior configuration or routing discovery operations. Moreover, our proposed algorithm does not require or include any location finding or positioning operations. The design of CEERA allows it to perform equally in the random deployed network.

The remainder of this paper is organized as follows. Section II describes the underlying network, deployment, traffic and energy models. Section III explains the design of CEERA. In section IV, we present and analyze the performance numerical results. Finally, we conclude the paper in section V.

II. MODELS, ASSUMPTIONS, AND PERFORMANCE MEASURES

In this section, we describe the underlying network model and other related models, including: deployment, traffic, and energy models. We also present our assumptions on the specification of sensor nodes and type of messages exchanged in our network. Main performance measures of the study are also discussed and explained.

A. Network Model

In any WSN, data being sensed by the nodes in the network must be transmitted to a control center or BS, where the end-user can access the data. There are many possible models for such networks, we consider a sensor network where: 1) The BS is fixed at a far distance from the sensor nodes. 2) The sensor nodes are homogeneous and are energy constrained with uniform energy. 3) Nodes have no location information. 4) Not all nodes are able to reach BS. 5) Symmetric propagation channel: that means the energy required to transmit a message from node *A* to node *B* is the same as the energy required for transmitting a message from node *B* to node *A* [2][3]. We also assumed that nodes are located in Cartesian coordinates and the BS is located at a fixed location (*O*: Origin, *C*: Center, *A* and *B*: Random locations). Nodes are randomly distributed and positioned across a Cartesian coordinate grid with each node is identified by an *ID* number as shown in Fig. 2. A given number of nodes *S* are distributed randomly around the BS in a square region of side length equals 50 meters. For every node of the $S=2^M$ nodes, we assign a fixed binary address of *M* bits. Limiting the number of nodes to *S*, limit the address size in data packet to be M=Log(S) bits for both the massage source node and transient node.

The transmission range of the base station is unlimited and can cover the entire network area. Hence, BS's signals are receivable by all nodes in the network. In the other hand we limit the transmission range of all sensor nodes to a given number equals D_{max}.

B. Deployment Model

Sensor node deployment problems have been studied in a variety of contexts. Many algorithms were proposed for the deployment of WSNs in the literature. In general, deployment is either **random** or **deterministic**. In random deployment**,** sensor nodes are deployed by air-dropping them or throwing them randomly in a target area. In contrast, in the deterministic deployment sensors are placed at pre-determined locations. Protocols for self-configuration of a randomly-deployed network may not be well suited for a deterministically-deployed sensor network. Similarly, data dissemination algorithms designed for deterministic sensor networks may not perform well when used in randomly-deployed sensor networks

The random deployment scheme is commonly used and more realistic strategy in most of WSNs applications. Our research is based on random deployment, where sensors are distributed randomly in a target area of size 50*50 meters. Ns2 (Network simulator2) has a built in utility module for generating random network topology for wireless sensor network. We used this module to assign a random location for each node in our network. Resulted topology is shown in Fig. 2.

The base station location plays a significant role in routing algorithm performance. More specifically, for a given $D_{max,}$ number of nodes within this distance to the base station is a key parameter that has a significant impact on the network operational lifetime. The greater this number, the higher the throughput. We experimented different locations for the base station including: the origin O:(0,0), the center C:(25.25)and two random locations A:(22.97, 31.79) and B:(8.92, 4.57).

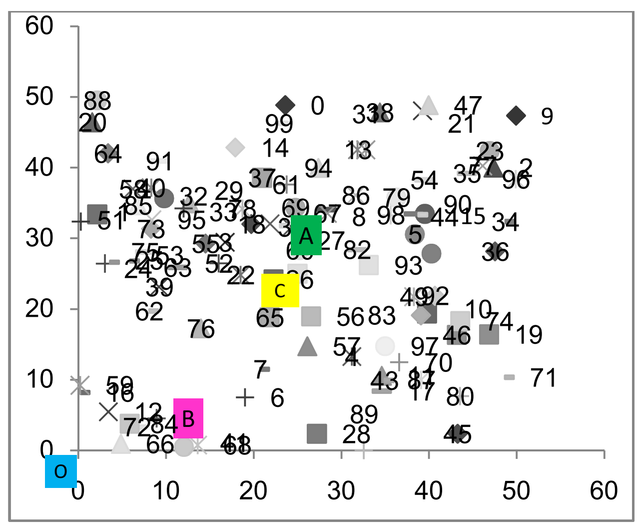

Fig. 2. The random network topology and multiple locations of the BS are shown.

C. Traffic Model

In our model, the arrival process of a new massage is characterized by Poisson process. The inter-arrival time between message arrivals moments is environment dependent. We studied network performance for different values of this parameter.

D. Energy Model

An important consideration in sensor networks is the amount of energy required for sensing, computation, and communication. Different assumptions about the radio characteristics, including energy dissipation in transmit and receive modes, will change the performance outcomes of routing protocols. In our work, we use a radio model similar to the radio model discussed in [2].

E. Specification of Nodes and Messages

We adapt the general component of a sensor node, where a node is decomposed of the four basic components: sensing, processing, transceiver, and power units. The additional application-dependent components such as a location finding system, power generator, and mobilizer are not considered.

For data messages, every data message (packet) has its unique identification number (*ID*) represented in *X* bits. Thus, up to 2^x different messages can be generated and transmitted simultaneously by a node before it refreshes its counter. The size of message content (data) is also limited to *K* bits. Every data message in our network contains: M-bits source node address, M-bits address for every transient node (optional), K-bits data, and X-bits message ID. In total, a data message contains *[M+K+X]* bits. Also, an acknowledgment packet (ACK) is decomposed of source node address (M-bits), and message ID (X-bits).

F. Performance Measures

In this subsection, we define a set of performance measures used to describe network performance. Our main performance measures are:

•Throughput: Number of successful transmissions to the base station.

•Delay: The time difference between message transmissions moment at the source node until the time moment it received by the base station.

•Delay Time Jitter (DTJ): The variation in inter-packet arrival time. It shows the variation of a metric (delay) with respect to some reference metric (average delay). A high value of DJT indicates that large variation between inter-packet arrivals.

•Total Energy dissipations: The total amount of energy dissipated from all nodes in the network.

•No. of dead nodes: No of nodes depleted of energy

•First Node to die lifetime (FND): Indicates the duration for which all the network nodes are fully functional. For some sensitive applications such as intrusion and fire detection, it is important to know when the first node dies.

•Beta of nodes to die lifetime: Total number of messages received until a β fraction of the nodes die. This indicates the amount of information collected until that time [4].

•Half of the Nodes Alive (HNA) lifetime: It indicates the duration of time for which only the half of nodes in the sensor network are alive.

•Last Node to die lifetime (LND): This measure denotes the duration for which all nodes in network dies.

•Redundant (duplicated) Arrival (DA): This measure shows number of duplicated arrival of messages to the base station. Duplicated arrival is not preferred as it causes extra dissipation of energy. We include this measure to test CEERA's ability to limit and prevent redundant arrivals of the same message through transient transmission.

•Congestion (Overhead): Congestion occurs when there is too much traffic on the network and the offered load exceeds the capacity of a data communication path.

We assume that congestion occurs when a node receives the same data message more than (n) times, where n is a given threshold value for number of re-transmissions. It is undesired to consume energy for receiving the same message or block memory for storing the message while many of the neighboring sensors are carrying out the transmission of that message. One of the objectives of our simulation study is to evaluate CEERA's ability to minimize and control congestion, because it affects both the WSN overall energy and memory. We introduced a measure called duplication factor. The value of this measure represents the maximum number of duplicated messages a node can receive before it deletes the message and releases the allocated memory. Through simulation, we studied the impact of this parameter value on network performance.

III. CEERA'S LEARNING SCHEME DESIGN

This section presents the novel design of a cooperative energy-efficient routing algorithm (CEERA). The design is based on the cooperative learning among sensors nodes. In CEERA, nodes cooperate in learning from each other in order to have an efficient delivery of data to the base station. Data transmission is cooperative from node to node until it received by the *BS*. The *BS* sends an acknowledgement for each received message. The *BS* transmissions are received by all sensor nodes. An acknowledgment includes important information for controlling both message storage and retransmission. When a source node decides to transmit its local data, it generates a packet with a unique message *ID* and transmits the packet after appending its ID_s in the header of the message. Also data message is flagged to be transmitted in either source-route mode or cooperative mode. Based on its energy level, a node may not participate in data transmission if its current energy is less than a predefined energy threshold (E_{min}).

The logic of CEERA that is implemented in each node is presented in the below flowchart, Fig. 3. Mainly, data transmission from a source node *s* can be direct to BS if the distance between *s* and *BS* is less than or equals D_{max}. Otherwise, transmission is cooperative.

In Cooperative transmission, each transient node *t* that receives the packet will carry out the following steps:

1) Calculates the *ID* difference as: $ID_d = ID_t - ID_s$: where ID_t and ID_s are the identification numbers (IDs) of transient and source nodes respectively.

2) Starts a timer counter with value=ID_d*scale factor

3) Listens to *BS*'s ACK, and periodically decrements its timer.

If the BS acknowledgment is not received within the timer value, the transient node retransmit message and append its address to the address list of transient nodes. This process is repeated by every transient node until BS acknowledgment (ACK) is received. Upon receiving the ACK, all nodes clear the call and reset their counters.

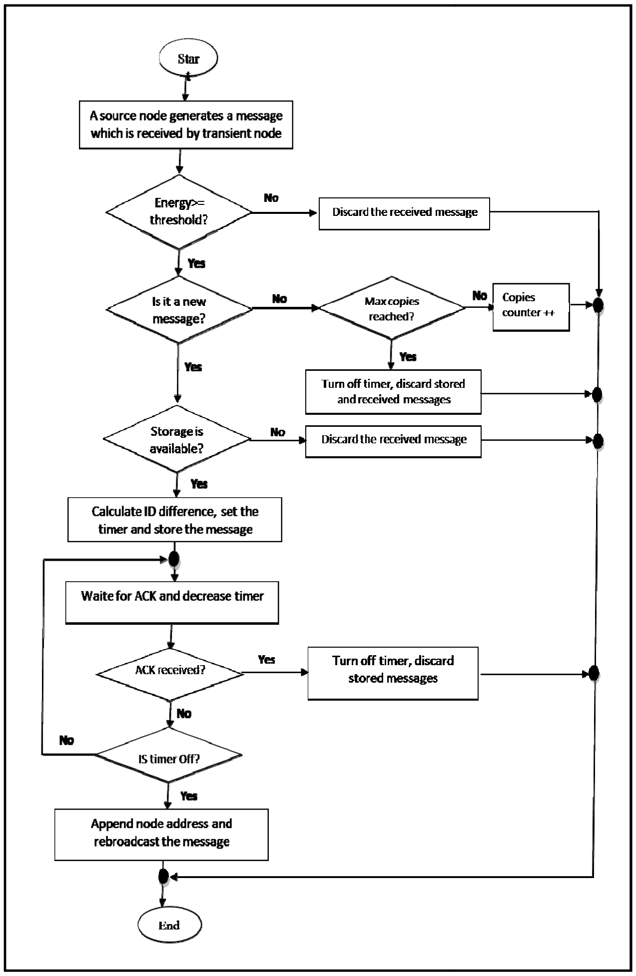

Fig. 3. A flowchart representing the design of CEERA.

Based on the above described steps, CEERA works as an adaptive distributed transmission and scheduling scheme which specifies relatively simple local actions to be performed by individual nodes in a WSN for routing. Each node adapts its local operations over time in response to the status and feedback of its neighboring nodes and BS ACK. Although, the adaptive scheduling defined by these local interactions achieves optimal global routing results.

IV. Performance Results

We implemented our own event-driven simulation program to test the performance of CEERA. The program was written in C++ programming language. Several development tools were used in this experiment. Mainly, we used Ns-2 to generate random network topology. To allow randomness, we used a true random numbers generator software offered by RANDOM.ORG [20]. This tool is mostly used for random sampling and as an input for the simulation experiments. Using [20], the generated numbers comes from atmospheric noise, which is for many purposes better than the pseudo-random number algorithms that are typically used in computer programs and are provided by many integrated development environments (IDEs) today.

We aimed at studying the impact of varying the **scalar factor**, **D_{max}**, **buffer size**, and **duplication factor** over the collected performance measures including: throughput, delay, DTJ, memory occupation per node, energy dissipation per initial energy, no. of died nodes, FND, BND, HNA, LND, Hop count, congestion/overhead, and duplicated arrivals. These performance measures were evaluated under different locations for the base station. This section presents some of these results.

Table I shows performance results of varying scalar factor for a given simulation input and 40.000 simulation messages, a buffer size=20, a mean inter-arrival time=0.5, an initial energy/node=101e+7, a duplicate factor=5, and D_{max}= 10 m. We extract results for scalar values: 0, 0.1, 0.5, 1, 2, 5, and 10.

It is shown that the zero value for the scalar results a poor performance as CEERA behaves similar to flooding algorithm that forwards every message received. The non-zero scalars have a positive impact over throughput for all BS locations compared to zero scalar. However, a higher scalar value does not always mean higher throughput. It is important when determining scalar value is to balance between our tendencies to save the retransmission energy, minimize delay caused by scalar factor, and utilize the available node resources. The optimal value for the scalar depends on the underlying network state and type of application. For our network, the best scalar value is between 0.1, 0.5 and 1 as it has the best throughput, increase storage sharing and also less delay than other values. Upper scalar values (2, 5, and 10) reduces throughput, minimizes memory sharing, and has a very high delay. It causes large message loss due to the memory shortage as a result of the long duration of blocking but not frequency of blocking. As expected, scalar factor is directly proportional to delay and delay time jitter. Values of delay and DTJ for scalars 0.1 and 0.5 are reasonable compared to the improvement in network throughput.

TABLE I
Performance results of varying scalar factor

The BS Location	Performance Factors	Scalar Factor						
		0	0.1	0.5	1	2	5	10
C	Throughput	4703	15151	15147	15149	15115	14911	14795
O		2849	5677	5677	5691	5700	5709	5709
A		4608	16829	16828	16824	16740	16600	16551
B		4144	7567	7567	7568	7569	7564	7560
C	Delay	0.00023	2.81936	14.0662	28.2405	60.2757	179.097	338.65
O		0.000271	2.86646	16.8269	30.4126	55.9837	89.3468	123.502
A		0.00	2.53	12.60	25.34	53.87	160.13	313.35
B		0.000192	1.84439	11.3982	19.1129	35.2904	54.8282	75.9604
C	Delay Time Jitter	0.000117	3.82722	19.1394	38.3072	82.3954	275.467	529.082
O		0.000263	6.10709	37.7896	73.5379	142.987	247.34	360.592
A		0.00	3.87	19.30	39.07	82.48	257.99	514.29
B		0.000203	5.17728	32.673	61.2812	118.92	211.417	337.255
C	Hop count /message	10	2	2	2	2	2	2
O		6	2	2	2	2	1	1
A		13	2	2	2	2	2	2
B		5	1	1	1	1	1	1
C	Duplicated Arrival	11007	21	24	22	34	88	80
O		2958	29	28	17	8	4	2
A		12939	0	0	2	63	89	45
B		3633	0	0	0	0	0	0

The location O is at (25,25), C is at (0,0), A is at (22.97, 31.79), and B at (8.92, 4.57). For a given D_{max}=10, No. neighbor nodes to the BS equals 18, 7, 20, and 9 for locations C, O, A, and B respectively.

Hop count is improved with the non-zero value for the scalar. A deep observation for the simulation shows that the amount of energy dissipated by direct retransmission affects most of the nodes that connects network segment in early time. As a result for this, later messages follow longer paths to reach the base station which increases the average hop count. The table also shows that scalar prevents duplicated message arrival to the BS. Network "A" behaves similar to "C", while network "O" behaves similar to "B" as they have similar conditions. An optimal value for scalar factor preserves energy, utilizes the available memory, with minimum delay.

We studied WSN performance of CEERA with various values of D_{max}. Figure 4, shows the WSN throughput (in terms of number of messages as a function of D_{max}. As shown, the highest recorded throughput is for BS at (A) which has the highest nodes density around BS. Increasing D_{max} increases throughput to a certain degree, minimizes delay, delay time jitter and hop count but it maximizes no. of duplicated arrivals.

For buffer size, it's expected that buffer size is proportional to throughput, and inversely proportional to delay, conjunction, and duplicated arrival. Maximizing buffer size allows more messages to be stored and routed later. We extracted results for buffer size values: 5, 10, 15, and 20. Simulation shows an increase in delay and DTJ for network "B" and "O", this is because more messages are

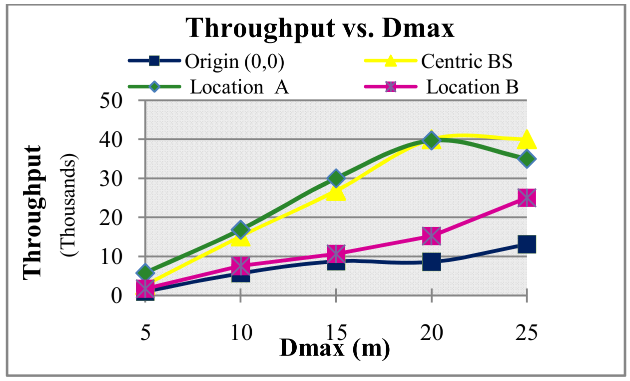

Fig. 4. Throughput vs. D_{max} (in meter) for different BS locations.

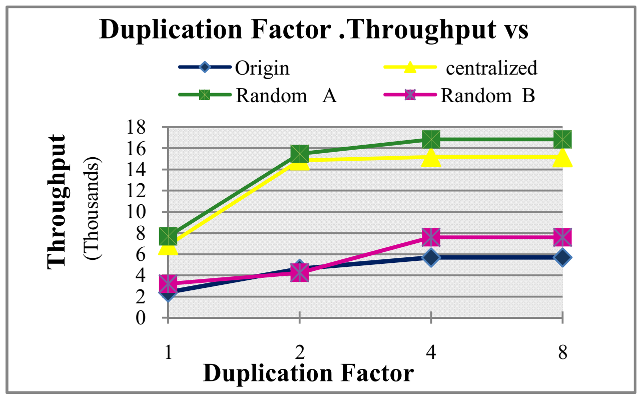

Fig. 5. Throughput vs. duplication factor for different BS locations.

able access BS after we increased storage of transient nodes. Simulation shows a minor change in throughput for increasing buffer size from 10 to 20, which implies that CEERA's efficiency is not restricted that the amount of memory. For all monitored networks, it's sufficient to include a realistic storage area and no need to extra storage.

The goal of introducing duplication factor in this research is to save memory by limiting long message storage while it stored by other neighbors. Duplication factor must be selected so that it avoids message loss and saves the available storage. When duplication factor equals r, it means that a message is discarded by a transient node when it received r times. A small value for duplication factor causes message loss, since message deleted quickly. Fig. 5 shows the impact of maximizing the value of duplication factor from 1 to 4 improves throughput for all networks. This significant improvement does not continue when duplication factor is increased to 8.

Furthermore, we studied the performance of CEERA extensively when compared to other algorithms. Simulation shows a significant improvement in energy usage in routing with CEERA. CEERA outperforms Flooding 15, 27, and 41 times. Also, CEERA achieves over a factor of 1.34 and 1.26 reduction in energy dissipation compared to Minimum Transmission Energy (MTE) scheme [6] for some BSs' locations.

V. CONCLUSION AND FUTURE WORK

Routing in sensor networks is a promising research area. Applications of WSNs show how it is important to design protocols and algorithms for wireless networks to be bandwidth and energy efficient. In this research, we proposed, designed and evaluated the performance of a learning scheme for energy aware routing algorithm for wireless sensor networks.

We designed CEERA to meet the following design criterion:

- Ease of deployment: In order to ensure that the nodes can be easily deployed in remote, hostile, or difficult areas.
- Minimum configuration: In CEERA, no prior knowledge or configuration is needed to make routing decision. A node determines wither to cooperate in retransmission the received message or to discard it locally, without exchanging more control messages to provide routing information. The only used control message is a small size BS ACK message.
- Minimum delay: Minimizing the latency caused by CEERA by selecting appropriate scalar factor value.
- Utilizing the available storage: we assumed sensors are equipped with a limited memory size. We introduced a factor, called duplication factor, to manage the use of the memory resource.

We evaluated CEERA performance with various operational parameters and studied its behavior from different perspectives. Our novel algorithm can be extended in different ways. Some of these are: optimizing CEERA's by introducing zero scalar factor for key nodes (BS neighbors), finding a method for optimal factors selection and evaluation, incorporating data aggregation to minimize energy dissipation and allowing node mobility.

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