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An Intelligent Routing Approach for Wireless Sensor Networks

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***Abstract*—Wireless sensing technology becomes a new scientific instrument for physical and environmental monitoring. The technology involves deploying a large number of tiny sensor nodes that cooperatively sense and report a specific condition at various locations to the base station. This class of applications faces many challenges, mainly caused by communication failures, storage and computational constraints and limited power supply. Therefore, sensing applications require intelligent, energy-efficient and self-organizing approaches. This paper proposes a novel intelligent routing approach for wireless sensor networks (WSNs) that achieves between 25%-50% energy saving compared to the existing WSNs' routing algorithms. It also improves the overall performance of WSNs for real world applications.**

Keywords—Wireless Sensor Networks; Intelligent Routing Approaches; Energy-Efficiency; Simulation and Performance Analysis

I. INTRODUCTION

Wireless Sensor Networks (WSNs) present a revolution in the field of wireless communication and embedded systems as they allow new generations of applications in many areas such as environmental monitoring, military and security, health care, structural-health monitoring, intelligent transportation systems, Internet of Things (IoT), and as a part of many smart systems such as smart cities. A WSN consists of thousands of very small stations called sensor nodes. The main function of sensor nodes is to monitor, record, and notify a specific condition at various locations to other sensor nodes and the end users [1][2][3][4]. Sensor nodes are battery-powered devices with sensing, communication and processing capabilities, as shown in Figure 1.

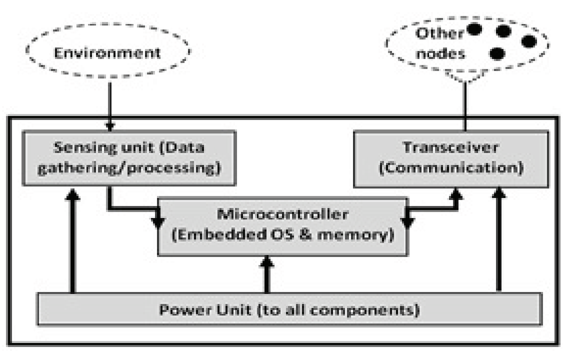

Fig. 1. Typical hardware components of a sensor node in wireless sensor networks

Wireless sensor networks pose their unique challenges due to the lack of a central entity for organization, sensors' limitation, mobility of participants, and limited range of wireless communications. Besides, in most of the WSN applications, sensors are deployed flexibly and quickly with minimal effort eliminating the need for physical backbone infrastructure. The scarcest resource in wireless sensor network is energy [5]. The most energy-consuming operation is communication and rout discovery. Therefore, finding an intelligent routing approach with energy-efficiency and self-organizing property is an important research problem in wireless sensor networks.

In WSN, data transmission is performed in multi-hop fashion, from one node to another toward the base station, using the short range broadcast medium node. This form of communication possibly floods the network with a large number of data packets due the multiple broadcasts by sensor nodes in the network. Thus, conserving sensor node battery power during route discovery and/or data transmission operations is a significant consideration when assessing the lifetime of the sensor nodes in a wireless sensor network [1][2][3][4].

Computational Intelligence (CI) have been successfully used in recent years to address various challenges such as optimal deployment, data aggregation and fusion, energy aware routing, task scheduling, security, and localization. CI provides adaptive mechanisms that exhibit intelligent behavior in complex and dynamic environments like WSNs. It brings about flexibility, autonomous behavior, and robustness against topology changes, communication failures and scenario changes [5]. There are many intelligent routing protocols which contribute to the optimization of network lifetime in wireless sensor networks. Most of these algorithms provide adaptive mechanisms that exhibit intelligent behavior in complex and dynamic environments like WSNs [5][6][7]. With a view to prolonging network lifetime, this paper proposes a novel intelligent routing approach that achieves between 25-50% energy saving than the existing routing methods for WSNs. The introduced routing protocol in this paper allows the transient sensor nodes to response intelligently for receiving data packets from source nodes, where in the packets are targeted for receipt by a base station. The sensor node, responsive to receiving the packet, implements a set of cooperative packet routing operations for conditional re-transmission of the packet to the base station.

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The rest of this paper is organized as follows: Section II presents the detailed design of our approach. Section III discusses the design of our simulation experiment. In section IV, we present simulation results. Finally in Section V, we conclude our findings and provide future work.

II. Intelligent Routing Approach with Energy-Efficiency for Wireless Sensor Network

In this section we discuss the design of our routing approach and highlight its major intelligence features.

At beginning, we assume that our sensor nodes are typical and homogenous. We assume that sensors include similar components to those presented in Fig. 1. Additional application-dependent components such as a location finding system, power generator, and mobilizer are not considered. For data packets, every data packet has its unique identification number (*ID*) represented in *X* bits. Thus, up to 2^x different packets can be generated and transmitted simultaneously by a node before a source node refreshes its counter. The size of packet content (data) is also limited to *K* bits. Every data packet in our network contains: M-bits source node address, M-bits address for every transient node (optional), K-bits data, and X-bits packet ID. In total, a data packet contains *[M+K+X]* bits. Also, an acknowledgment packet (ACK) is decomposed of source node address (M-bits), and packet ID (X-bits).

The proposed approach in this paper is *cooperative*. Hence, a packet transmitted from the source node that originates it to the base station in multi-hop fashion from one node to another. The other nodes that cooperate in transmitting the packet from the source node to the base station, by rebroadcasting it, are called transient. When a packet is rebroadcasted, it is received by its 1-hop neighbors within a maximum transmission distance, called D_{max}. However, in our approach, the base station transmissions can be received by all sensor nodes. We assume that the base station sends an acknowledgment for every received packet. Acknowledgments include important information for controlling both packet retransmissions and storage by transient nodes.

When a source node decides to transmit its sensed data, it generates a packet with a unique ID and transmits the packet after appending its ID. Our approach achieves energy-efficiency by minimizing packet retransmission caused by transient nodes. It allows the transient sensor nodes to response *intelligently* for receiving data packets from source nodes. It implements a set of cooperative packet routing operations for conditional re-transmission of the packet to the base station. The conditional re-transmission of the packet is based on a set of randomized packet re-transmission criteria including: network-based parameters, the characteristics of data packets, and the available resources in the sensor (e.g. memory and energy). This conditional retransmission controls and delays the packet retransmission by a variable time period, calculated as a function of multiple factors that are carefully chosen to prolong the lifetime of sensor nodes, ensure network connectivity, and guarantee substantially optimal energy **usage of the overall network.**

Our approach maximizes the lifetime of sensor nodes by considering the residual energy level as a major criteria for the participation in the cooperative packet routing. Based on its energy level, a transient node may not participate in data transmission if its current energy level is less than a predefined energy threshold (E_{min}). This energy threshold is set to ensure substantially optimal usage and lifetime of the sensor node in the wireless sensor network.

Fig. 2 explains the logic of our approach. The transient sensor node, responsive to receiving the packet, estimates how much operational energy remains in the sensor node. If the determined amount of energy meets a configurable threshold, the transient sensor node implements a set of cooperative packet routing operations for conditional retransmission of the packet to the base station. The conditional re-transmission of the packet is based on a set of randomized packet re-transmission criteria.

Packets transmission can be direct from the source node *s* to the base station (BS) (if the distance between the source node and the base station is less than D_{max}). If not, transmission is cooperative. Each transient sensor node *t* in the network $(N)_s$ who received the transmitted packet will carry the following: 1) Calculates the ID difference as $=ID_d = ID_t - ID_s$, 2) Starts a timer counter with value ID_d * scale factor, and 3) Listens to BS's ACK, and periodically decrements its timer.

If the acknowledgment is not received within the timer value, the transient node appends its address to the address list of the packet and retransmits the packet. This process is repeated by each node until a base station's ACK is received. Upon receiving an ACK, a transient node clears scheduled operations for the acknowledged packet, resets its counters, and discards the packet.

Sensor nodes have limited memory space. Therefore, it is able to store a limited number of packets. Our approach is also intelligent in that it considers and utilizes the available storage in transient nodes in different ways. First, upon the receiving a new packet, a transient node checks its available memory and a predefined space threshold. If no enough memory to store the new packet, the packet is discarded in order to keep the available node resources for its own packets transmission.

Second, it uses a duplication factor in order to avoid loop invariant. It avoids processing and storing a packet that is stored and processed by many neighboring nodes. Upon receiving a previously received packet (an old packet), a transient node increments the duplication counter that relates to the duplicated packet. A transient node discards the duplicated packet and reset all timers if the duplication counter reaches a maximum duplication factor.

Our approach is also intelligent in that it uses the stored route in the exchanged packet for route back. It also uses it in speculating the hop distance to the neighboring nodes and the base station. Accordingly, in order to minimize the overall delay, the timer value is set to zero in the key nodes that are at 1-hop distance from the base station.

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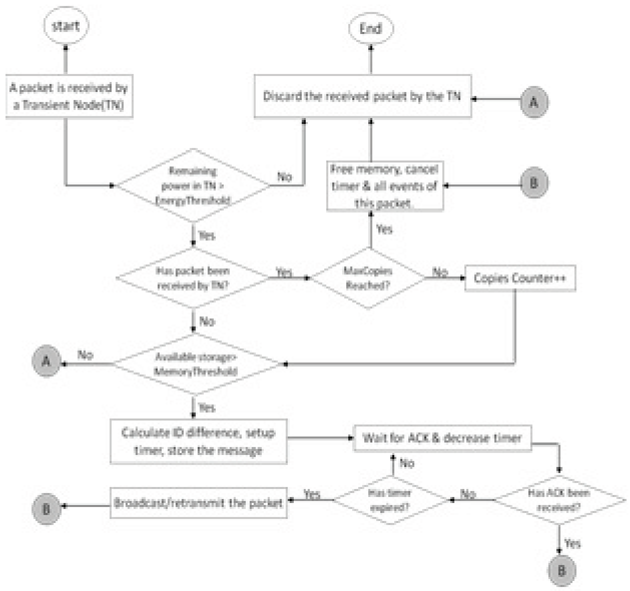

Fig. 2. The implemented routing operation in the transient sensor nodes

III. Performance Evaluation and Results

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 the underlying network and sensor nodes. The main performance measures are also discussed and explained.

A. Simulation Setup

We used *unit disk graph* (UDG) to model and study the underlying network. In UDG, Nodes are located in the Euclidean plane and are assumed to have identical (unit) transmission radiuses. Consequently, an edge exists between two nodes if and only if their Euclidean distance is not greater than one (or a unit of length). The UDG allows modeling a flat environment with network devices equipped with wireless radios, all having equal transmission ranges. Edges in the UDG correspond to radio devices positioned in the direct mutual communication range [4][9].

We consider a sensor network where: 1) The BS is fixed, 2) sensor nodes are homogeneous and are energy constrained with uniform energy, 3) sensors have 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 packet from node *A* to node *B* is the same as the energy required for transmitting a packet from node *B* to node *A* [2][3].

We implemented our own event-driven simulation program to test the performance of our approach. 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. The block diagram for the simulation program is shown in Fig. 3. It shows the main events that are included and scheduled in event list. The initialization routine initializes network topology, network and simulation parameters. It also initializes event list by scheduling the first message arrival event. The execution of message arrival event schedules the message generation event and next message arrival at exponential t time for a randomly selected node i. Then the program applies our routing algorithm by scheduling and executing the suitable events. The state of system is updated within events execution. At the end of simulation, the simulation program reports the performance results.

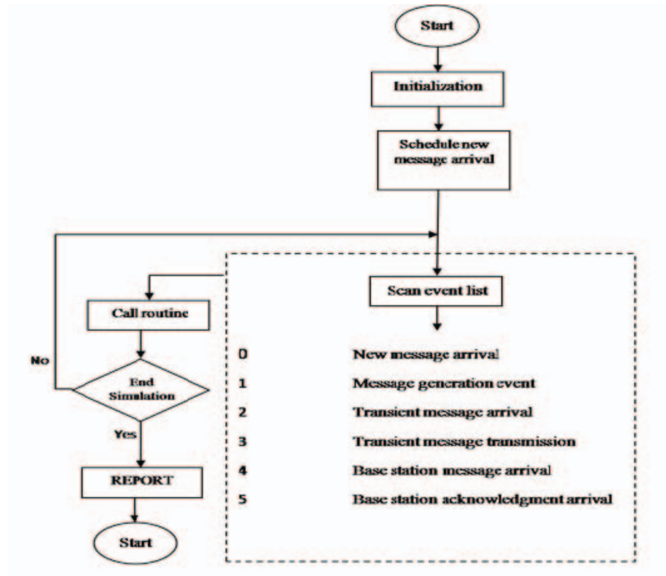

Fig. 3. Diagram of the event-driven simulation program

For the deployment model, in our simulation, we consider a *uniform random deployment model*. For a given 2D square field of area *A*, we generate a total of *N* nodes. In the uniform random deployment, each of the *N* sensors has equal probability of being placed at any point inside the given deployment field. Consequently, the nodes are scattered on locations which are not known with certainty. For example, such a deployment can result from throwing sensor nodes from an airplane. In general, a uniform random deployment is assumed to be easy as well as cost-effective. WSN applications often prefer random node deployment, which is why we included it in assessing the performance of our algorithms [10].

We evaluate the performance with different input values for the numbers of nodes *N*, the transmission range D_{max}, and the deployment area *A*. 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}.

In our model, the arrival process of a new packet is characterized by Poisson process. The inter-arrival time between packet arrivals moments is environment dependent. We studied network performance for different values of this parameter. An important consideration in sensor networks is the amount of energy dissipated for sensing, computation, and communication. In our work, we use a radio model similar to the radio model discussed in [2] and [11].

The base station location has a significant impact over the performance of any routing algorithm. 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

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operational lifetime. The greater this number, the higher the throughput. We examine the impact of the base station location over the performance our proposed approach. We consider the following different settings: 1) A random network deployment with a centralized base station, and 2) A random network deployment with a random base station placement inside the deployment area. Fig. 4 shows the considered different base station locations in our simulation.

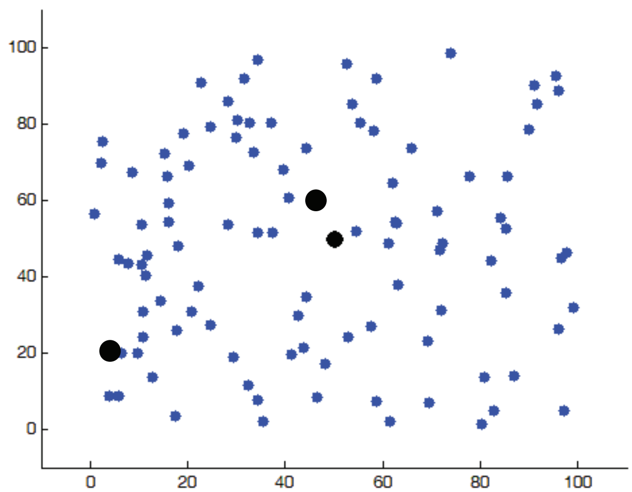

Fig. 4. An Example of a randomly deployed network with two different locations for the base station

B. *Performance Measures*

In our simulation, we evaluate many important performance factors. Our goal is to achieve the optimal energy saving without affecting the overall WSN operations. Our main performance measures are as follows: Throughput (Thr), Delay (D), Delay Time Jitter (DTJ), the Total Energy dissipations (E), and number of dead nodes. We also include other measures like: 1) First Node to die lifetime (FND) to indicate the duration for which all the network nodes are fully functional. 2) Beta of nodes to die lifetime: to indicate the total number of packets received until a β fraction of the nodes die: to indicate the amount of information collected until that time. 3) Half of the Nodes Alive (HNA) lifetime: to indicate the duration of time for which only the half of nodes in the sensor network are alive. 4) Last Node to die lifetime (LND): to record when all nodes in the network died.

Furthermore, we measured the number of redundant (duplicated) message Arrival (DA) to the base station in order to test our approach's ability to minimize redundant arrivals of the same packet through transient transmission. For Congestion (Cong.), we assume that congestion occurs when a node receives the same data packet more than (n) times, where n is a given threshold value for number of re-transmissions. One of our objectives of our simulation stud is to evaluate routing algorithm ability to minimize and control congestion, because it affects both the WSN overall energy and memory utilization (MU). We introduced a measure called duplication factor which gives the maximum number of duplicated packets a node can receive before it deletes the packet and releases the allocated memory. Through simulation, we studied the impact of changing these parameters over the network performance.

C. *Simulation Results*

Given simulation input of 40.000 Simulation packets, 20 buffer size, inter-arrival time = 0.5, initial energy per node = 101e+7, Duplicate factor=5, and D_{max}= 10m, we extract results scalar values: 0, 0.1, 0.5, 1, 2, 5, and 10. Performance results show that our proposed method achieves a significant performance improvement up to ten times in the life time of half of the WSN nodes compared to the existing routing protocols for WSNs. This improvement is valid when employing our protocol in various settings for the underlying network.

The value of scalar factor has a direct influence on end-to-end delay since it controls the timer value (waiting period). Also, has a positive effect on energy dissipation. It delays the transmission of the received message for certain amount of time, within that time a message might be received and acknowledged by the BS which save energy and minimizes the overhead caused by this re-transmission. It also saves energy that would be dissipated if the message transmitted and received by neighbor nodes. In the other hand has a negative effect on memory occupation as the message stored for long time upon ACK re**ceiving or timer is turned off.**

Simulation shows that the zero value for the scalar results a poor performance since our approach behaves similar to Flooding algorithm, which 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. Simulation results in centric and origin base station settings are shown in TABLES I and II, respectively. TABLE III summarizes the overall impact of changing simulation variables over the major performance measures of the network.

TABLE I. PERFORMANCE RESULTS FOR NETWORK WITH A CENTRALIZED BS

Base station Location	**Center**						
Scalar Factor Value	*0*	*0.1*	*0.5*	*1*	*2*	*5*	*10*
Throughput	4703	15151	15147	15149	15115	14911	14795
Delay	0.00023	2.81936	14.0662	28.2405	60.2757	179.097	338.65
Delay Time Jitter	0.000117	3.82722	19.1394	38.3072	82.3954	275.467	529.082
No. of Died Nodes	98	97	99	99	99	99	99
FND	1359.84	2086.26	2094.39	2109.57	2168.79	2824.1	4198.88
BND	1739.01	4066.32	4098.71	4116.72	4284.27	4938.21	7410.86
HND	2373.44	5837.21	5708.44	5743.14	5601.44	7090.23	10597.2
LND	0	0	10208.6	9992.52	9893.33	11002.3	14042.4
Congestion	68179	9448	9468	9771	11003	10768	7295
Duplicated Arrival	11007	21	24	22	34	88	80
Hop count /message	10	2	2	2	2	2	2
Frequency Memory Occupation	100907	235434	235809	236096	224432	164275	120261

TABLE II. PERFORMANCE RESULTS FOR NETWORK WITH A BS LOCATED AT THE ORIGIN OF THE DEPLOYMENT FIELD

Base station Location	**Origin**						
Scalar Factor Value	*0*	*0.1*	*0.5*	*1*	*2*	*5*	*10*
Throughput	2849	5677	5677	5691	5700	5709	5709
Delay	0.000271	2.86646	16.8269	30.4126	55.9837	89.3468	123.502
Delay Time Jitter	0.000263	6.10709	37.7896	73.5379	142.987	247.34	360.592
No. of Died Nodes	98	99	99	99	99	99	99
FND	500.902	539.444	580.26	641.373	753.441	1279.06	1939.52
BND	527.825	673.546	779.148	1039.54	1096.15	1657.5	2814.23
HND	572.273	1196.28	1234.54	1495.2	2212.02	3044.87	6546.16
LND	0	6680.52	6300.32	6187.31	6885.03	9217.4	12440.3
Congestion	333092	82959	84943	82712	79559	65579	33306
Duplicated Arrival	2958	29	28	17	8	4	2
Hop count /message	6	2	2	2	2	1	1
Frequency Memory Occupation	105137	152899	140212	135639	128915	115978	102606

TABLE III. SUMMARY OF THE IMPACT OF VARYING SIMULATION VARIABLES OVER NETWORK PERFORMANCE

Input Variable	Variation Range	Thr	D	DTJ	Nodes' lifetime	MU	DA	Cong
SF	]0,1]	+	+	+	+	+	-	-
D_{max}	[5,20]m	+	-	-	-	+	+	+
Buffer Size	[10,20]	+	≈	≈	≈	+	-	-
Max Copies	[2,4]	+	+	+	-	+	+	+

Furthermore, we studied the performance of our approach extensively compared to other routing algorithms for WSNs. Simulation shows that our intelligent routing approach has a significant improvement in energy usage when compared to two routing protocols: Flooding and Minimum Transmission Energy (MTE). Our proposed approach outperforms Flooding 15, 27, and 41 times. Also, our approach achieves over a factor of 1.34 and 1.26 reduction in energy dissipation compared to Minimum Transmission Energy (MTE) routing protocol.

Fig. 5 and Fig. 6 show the performance results of our approach compared to the MTE and Flooding routing protocols in term of throughput and lifetime when the transmission range varies between 5m and 20m. Fig. 5 shows the performance of our routing protocol against flooding in prolonging the lifetime of network when half of the sensors in the network die. Fig. 6 shows the performance of our routing protocol against flooding in prolonging the lifetime of network when half of the sensors in the network die.

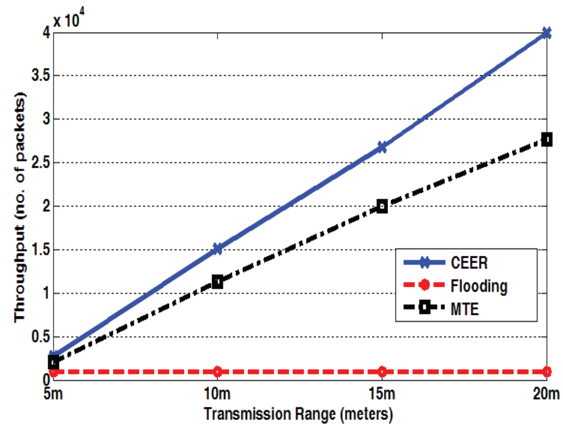

Fig. 5. The performance of our intelligent routing protocol against flooding and (MTE) routing protocols

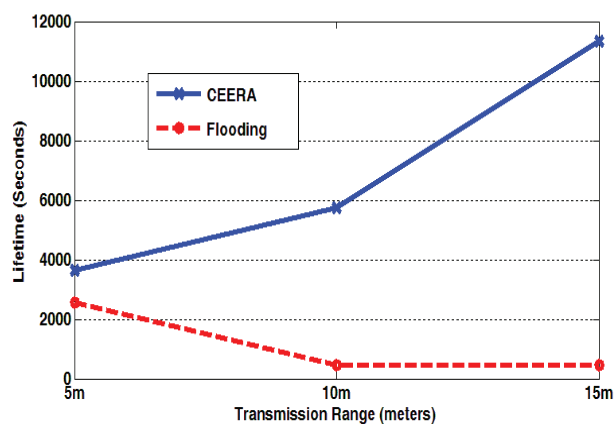

Fig. 6. The performance of our routing protocol against flooding in prolonging the lifetime of network when half of the sensors in the network die

IV. CONCLUSION

In this paper, we propose an intelligent routing approach for wireless sensor with a view of prolonging the lifetime of the network. Our protocol is expected to be very useful and applicable in most of the existing WSNs-based applications to minimize energy consumption and prolong the operational lifetime of the network; in particular for applications where accessing network sensors is either difficult or dangerous, such as extreme environments, highways, military field, and underground/underwater applications of WSNs. On the other hand, this approach is also valuable as it does not require any prior settings, route discovery operations, or location

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information while allowing scalability, and load-balancing among sensor nodes.

Our approach has zero-configuration overhead. Hence, nodes do not require a prior configuration, knowledge, or location determination to perform routing or make routing decision. A transient node makes a local decision to determine whether or not to cooperate in to retransmission of the received packet. In our approach, nodes do not exchange any control messages to provide routing information. The only used control message is a small-sized base station ACK packet. Additionally, our approach aims to achieve minimum delay by minimizing the latency caused by its conditional retransmission by selecting appropriate scalar factor value. It also utilizes the available node resources by including duplication factor and residual energy threshold in making routing decisions.

We evaluated the performance of our approach with respect to many performance factors and under different network scenarios. Moreover, we studied the performance of our approach extensively when compared to other routing algorithms for WSNs. Simulation shows that our routing approach has a significant improvement in energy usage when compared to two routing protocols: Flooding and MTE. Our proposed approach outperforms Flooding 15, 27, and 41 times. Also, our approach achieves over a factor of 1.34 and 1.26 reduction in energy dissipation compared to the MTE routing protocol.

There is still much work to be done in the area of protocols for wireless sensor networks. This research can be followed by some related studies, including: optimizing our algorithm by introducing zero-scalar factor for key nodes, finding a method for optimal factors selection and evaluation, incorporating data aggregation to minimize energy dissipation.

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