On Regulating Lifetime of a 3-sink Wireless Sensor Network Deployed for Precision Agriculture

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The main motivation behind this work is **regulating network lifetime** of a WSN deployed in an agricultural land. In this paper we have proposed one 3-sink WSN architecture to be used for precision agriculture applications. The objective of this paper is twofold; **to propose a model of WSN to be used for precision agriculture that prolongs network lifetime**, and **to regulate network lifetime through introduction of two parameters – neighbor density and effective network density**. Neighbor density is the measure of density of neighbors around a particular node. Here we have seen that at an optimum value of neighbor density, lifetime of a network reaches its pinnacle. However, regulating network lifetime through neighbor density requires the nodes to be deployed in grid fashion. For networks where nodes are deployed in random fashion, effective network density may be used as regulating parameter for prolonging network lifetime. In this paper we propose two routing schemes: KPS and Loop Free (LF)-KPS for network lifetime enhancement. The results show that LF-KPS in particular outperforms some well-known protocols by a considerable margin.

Keywords: Multi-sink wireless sensor network, Precision agriculture, Fermat point based data forwarding, Neighbor density, and Effective network density

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1. INTRODUCTION

Energy optimization and network lifetime enhancement in Wireless Sensor Network (WSN) has been an active research area during the present and major part of the past decade. Many energy efficient routing protocols had been proposed by researchers for the said purpose during this time. Although, most of the proposed protocols are for networks with a single sink, a few of them have been proposed for multiple sinks as well. It is beneficial to have multiple, redundant sinks in a WSN due to the following reasons:

(i) distributing the load of data collection to multiple sinks
(ii)reduction in sink hole problem
(iii)reduction in total number of hops encountered by a packet
(iv)providing infrastructure support over multiple interfaces, if required
(v) increase in overall network lifetime
(vi)eliminating single point failure

When it comes to forwarding the same packets to multiple sinks, Fermat point based data forwarding technique is suitable in order to achieve energy efficiency and enhanced network lifetime. Fermat point based data forwarding technique is suitable for multi-sink or multi-target network [Ghosh et al. [2015]]. A Fermat point based data forwarding technique ensures maximum network lifetime by minimizing energy consumption, as it can guarantee a minimum overall transmitting distance for packets from source to multiple sinks [Ssu et al. [2009]]. According to the radio model proposed by Ghosh et al. [2015], of all the factors affecting energy consumption in WSN, the distance between the nodes is the one that plays the vital role. The radio model used by the authors show that energy consumption for transmission varies super linearly with the distance between the communicating nodes.

Of the different application domains where a Wireless Sensor Network (WSN) may be deployed, precision agriculture (PA) has become a prominent one. It has been seen that introduction of WSN in agricultural activities have had a positive effect in reducing the installation cost of the network. Introduction of wireless technology eliminates up to 80 percent of the cost incurred due to wiring [Wang et al. [2006]]. In PA the nodes report the acquired measurements to a collector point or sink. In many other cases, a sensor node is used for data aggregation as well and then the aggregated data is transmitted to the sinks [Wark et al. [2007]]. In both the cases, however, the presence of multiple sinks may turn out to be a necessity due to the above mentioned points.

In this paper we have proposed a model for measuring agricultural data through sensor nodes and transmitting them to three different sinks. We present two protocols for data forwarding. The first proposed protocol for transmitting data to different sinks is based on one of our previous works - KPS protocol [Ghosh et al. [2016]] and the second is an improvement upon the same protocol – Loop free KPS (LF-KPS) protocol – which we propose in this paper. Our first objective is to prove that our proposed model prolongs network lifetime as compared to some of the well-known protocols for WSNs. Our second objective is to introduce two parameters – neighbor density and network density – and then to regulate network lifetime of a WSN deployed for PA, by varying these two parameters.

The rest of the paper is organized as follows: in section 2 we have discussed some of the related works in the field of lifetime enhancement of WSNs. In section 3 we discussed the proposed theoretical model. Section 4 contains discussion about the results and finally we conclude in section 5.

2. RELATED WORKS

Grid deployment of the nodes had been recommended for many application areas of WSN. This is done to ensure enhanced lifetime of the WSN deployed [Galmes [2006]]. For applications like precision agriculture, the desired grid distance is to be less than 30 meters. Ferentinos et al. [2005] too kept the grid sizes as 30m x 30m in a precision agriculture environment. The main objective of authors here was finding optimal operation mode of each sensor node deployed in an agricultural field. However, the authors were concerned about the spatial density of the sensors deployed. They observed that spatial density for deployment would be cultivation specific and also depend upon the parameters to be measured. They proposed a genetic algorithm to find out the optimal operation mode of the nodes. In most of the agricultural applications, nodes are deployed in grid fashion to ensure enhanced lifetime of the WSN deployed [Galmes [2006]]. Díaz et al. [2011] however proposes nodes to be deployed in grid fashion with 20m x 20m grid size.

Over the years researchers have proposed various energy efficient routing protocols for WSN. [Akkaya and Younis [2005]] had done an extensive survey of different routing protocols in WSN. They have sub divided the routing protocols in the following genres : data centric, hierarchical, location based and QoS aware.

A classic example of data centric routing protocol is SPIN described by Heinzelman et al. [1999]. In this protocol, the data is named using meta-data or high-level descriptors. The main feature of SPIN is that data advertisement mechanism is used to exchange meta-data between the servers before transmission. In SPIN, each node has information about its immediate neighbors. In order to advertise meta-data ADV message is used, REQ message is used to request a particular data and DATA message is used for transmission of data. The disadvantage of SPIN is that advertisement mechanism doesn't ensure the delivery of data. Another important milestone in data centric approach came with the directed diffusion technique proposed by Intanagonwiwat et al. [2000]. Here a naming scheme is used to diffuse the data through the server. It uses an attribute-value pair for the data. These pairs are used on demand basis to query the sensors. If the path between the source and sink fails, path repairs are possible through this protocol. Since it is based on query-driven data delivery, it cannot be applied to all sensor networks.

A variant of directed diffusion was proposed by Braginsky and Estrin [2002] in the name of Rumor routing. In this protocol, the queries are routed to only those nodes which have observed a particular behavior instead of flooding the complete network. The concept of agents is used to flood events. Agents are basically long-lived packets that travel in the network to propagate information. In Rumor routing, a fixed path is maintained between the source and the destination. This routing protocol saves significant amount of energy.
We would like to discuss one more data centric protocol in this context. ACtive QUery forwarding In sensoR nEtworks (ACQUIRE), proposed by Sadagopan et al. [2003]. It views the entire WSN as a distributed database. It is suitable for complex queries that contain sub queries. Each node responds partially to the query forwarded by the sink according to pre-cached information. The nodes try to get information through their neighbors if local information is not up to date. And finally the information is sent by all nodes to the sink.

Coming to the hierarchical protocols, the first one to discuss is LEACH, proposed by Heinzelman et al. [2000]. It is one of the most prominent protocols for routing of packets in a WSN and acts as a base protocol for many other protocols. The LEACH protocol was developed for a homogeneous sensor environment and based on the concept of clusters. In LEACH protocol, all sensor nodes are grouped together in the form of clusters and all clusters have their respective cluster heads. Each cluster head is responsible to collect data from the sensor nodes within the cluster and forward it in the form of packets to the base station. The sensor nodes in LEACH protocol use amplification energy in order to transmit data between the transmitter and the receiver. The major drawback of the LEACH protocol was that a new cluster head was selected for every round which led to the formation of new clusters for each iteration. Also, in the LEACH protocol sensor nodes used same amplification energy regardless of the distance the packet travelled. Hence, there was an unnecessary routing overhead.

MOD-LEACH [Mahmood et al. [2013]] is an improvised version of the LEACH. MOD-LEACH limits the election of new cluster head for every round by considering the residual energy of the present cluster head. This protocol was developed in order to increase the throughput and lifetime of the sensor network by dual transmitting power levels and effective replacement of cluster heads when necessary. The MOD-LEACH suggests three modes of data transmission for a cluster based network:

a. **Intra Cluster Transmission** that allows cluster members to sense data and transmit it to the cluster head
b. **Inter Cluster Transmission** that deals with communication between two cluster heads
c. **Cluster head to base station transmission** which allows direct transmission from cluster head to the base station

According to the MOD-LEACH protocol the amplification energy required for inter cluster transmission and cluster head transmission is comparatively lower than the intra cluster transmission. Also, during its tenure if much energy is not spent by the previous cluster head and if the residual energy is greater than the specified threshold, then it continues to be the cluster head for the next round as well. This concept of different amplification energies for different types of transmissions and election of a new cluster head only when it is required saves a huge amount of energy.

As specified, a number of other hierarchical protocols too emerged from LEACH. Power-efficient GAthering in Sensor Information Systems (PEGASIS) by Lindsey and Raghavendra [2002] is also an improvised version of LEACH protocol. In PEGASIS protocol, the sensor nodes form chain to transmit data from source to sink. Each node that receives data from the previous node aggregates it with its own data and forwards to the node ahead in the chain. This process continues until the data is received by the base station. Greedy forwarding is used in order to construct the chain.

Another popular variation of LEACH was proposed by Smaragdakis et al. [2004] - SEP: Stable Election Protocol - for the heterogeneous WSN. Here, the nodes are equipped with different levels of energies and deployed randomly. This protocol suggests a stability period which is the interval of time before the first node dies. It is also a cluster based routing protocol where the cluster head is elected on the basis of the residual energy of each node within the cluster. In this protocol, the nodes are categorized into advanced nodes and normal nodes depending upon the energy of the node. The protocol considers two parameters of heterogeneity. The first one is the number of advanced nodes and the other one is the difference of energy between the normal nodes and the advanced nodes. According to this protocol, the probability of advanced sensor to become cluster head is higher than that of normal nodes. This is an efficient way to increase the stability period and hence increase the lifetime of the network. SEP protocol works well for both dense as well as small sized network. Threshold sensitive Energy Efficient sensor Network protocol (TEEN) protocol was designed to respond to sudden changes in sensed data [Manjeshwar and Agrawal [2001]]. It is a hierarchical protocol which uses a data-centric mechanism. The nodes are grouped into clusters and then one node acts as the cluster head. If the sensed data is beyond a certain range then only the data transmission starts and data is transmitted to the sink.

For discussing QoS aware protocols, we take Minimum cost forwarding approach [Ye et al. [2001]] and SPEED protocol [He et al. [2003]].

Minimum cost forwarding approach finds a path within a large network with minimum cost. This path is both scalable and simple. The cost function calculates cost on the basis of delay, energy consumption and throughput. The packet transmission takes place in two phases. In the first phase the nodes adjusts their cost values and in the second phase the packet is broadcast to the sink via minimum cost path. SPEED provides an end-to-end guarantee. In the SPEED protocol, each node has complete information about its neighbors. The key feature of this protocol is that it ensures a certain speed of packet transmission so that the end-to-end delays can be calculated. It helps in avoiding congestion in the network and provides real soft-time delay.

3. PROPOSED MODEL

The sensors are supposed to be deployed over a two dimensional Cartesian plane. As Figure 1 shows, we have assumed the shape of the agricultural field to be square or rectangular. On its three corners are three sinks. Nodes are deployed in a grid fashion. The size of the grid may vary from 20m x 20m to 40m x 40m, depending upon the nature and requirement of the application for node density. However, it is to be noted that the size of the sensor field remains the same. The changes in the grid sizes are to change the **neighbor density** of the sensor field and thereby study the effects of changed neighbor density on the lifetime of the deployed network. The effect of changed neighbor density on network lifetime has been discussed later in section 4.

The nodes would keep measuring the soil moisture level of the sites they are deployed and would report to the sinks when the value of soil moisture has gone down below the permissible threshold for the crop. As a result, only the affected patches of the land gets watered and not the entire land. This way, we can optimize the watering of the agricultural field and thereby can save water. Let us now discuss two of our protocols (i) KPS and (ii) Loop-Free KPS (LF-KPS) respectively.

KPS: When a sensor node deployed in a logical grid (as shown in Figure 1) measures the value of soil moisture to be less than the prescribed threshold, it sends the value of the measured soil moisture to all the sinks using the KPS algorithm [Ghosh et al. [2016]] - a Fermat point based data forwarding technique. A Fermat point based data forwarding technique ensures minimum distance traversal by a packet from source to different sinks for multiple targets [Song et al. [2005]]. Fermat point is that unique point within the boundary of a triangle or concave polygon, which ensures that the sum of all the vertices from that point to be minimum as compared to any other point within that triangle or polygon. The concept of Fermat point holds good, when none of the internal angles of the triangle/polygon is greater than 120 degrees.

For locating the Fermat point of a triangular/polygonal region, we have used the Global Minima Scheme - a novel minima based technique from one of our previous works described in [Ghosh et al. [2009]]. The polygon is formed by three sinks and one of the sensor nodes. We assume that we are aware of the coordinates of the sinks and all the sensor nodes. The node closest to the theoretical Fermat point is marked as Fermat node (FN). The sender would transmit through multiple hops to the FN. After a packet reaches FN, it is the responsibility of FN to transport the packet to the sinks. However, before a node acting as FN for one or more than one sender(s) could forward the packet to different sinks, data aggregation is carried out by the FN.That is, FNs are the aggregation points. It has been shown in our previous work [Ghosh et al. [2015]] how aggregation plays an important role in extending lifetime of a multi-sink WSN. In fact, bigger the value of aggregation factor (AGFACT) [Ghosh et al. [2015]] more would be the lifetime of the network with all other parameters remaining same.
In Ghosh et al. [2015] two different aggregation schemes have been proposed: (a) accepting n input packets each of size p and producing a single output packet of size p, and (b) accepting n input packets each of size p and producing a single output packet of size n x p. Scheme (a) is for those applications where the max, min, average values are required. Whereas, in scheme (b) every individual data is important. For the present work, we have used aggregation scheme (b).

The transmission of packets from source to sink takes place in two steps: (i) from source to FN and (ii) from FN to sinks. For both the steps, the next hop forwarder is selected using the κ-forwarding technique used in KPS algorithm. In κ-forwarding, each node calculates the forwarding potential (κ) of all its neighbors, before forwarding a packet. The one with the highest value for κ is selected as next hop forwarder. Forwarding potential κ_{ij} for a node i for a sink j is calculated as

$$\kappa_{ij} = resenergy_i / dist_{ij} \qquad (1)$$

where
$resenergy_i$ = residual energy of node i in milli-Joules
$dist_{ij}$ = distance between node i and sinkj in meters

Here we have shown that grid size can be varied to alter certain parameters and thereby increase network lifetime. In this paper we have introduced two different parameters: (i) neighbor density and (ii) effective network density. In the next section we will see how these parameters affect network lifetime.

For calculating energy consumption and network lifetime of the deployed network, we have followed the radio model proposed in Ghosh et al. [2015]. The main components of energy consumption as pointed out are for: (i) transmission (E_{TX}), (ii) forwarding ($E_{forwarding}$), (iii) reception (E_{RX}), (iv) sensing ($E_{sensing}$), (v) computing ($E_{computing}$) and (vi) idle listening ($E_{listening}$). There is a minute distinction between transmission and forwarding. Energy consumed by the source node for transmission (E_{TX}) comprises the components — $E_{sensing}$, $E_{computing}$, and $E_{forwarding}$. Relay nodes on the other hand need to receive a packet before they can further forward it.

Thus, E_{RX} and $E_{forwarding}$ are the components of energy consumption for relay nodes. Finally, we assume that when a node neither acts as sender nor as relay, then it is listening to the transmissions of its neighbors. The energy consumed for the said purpose is represented as $E_{listening}$. A node is considered to be in the "on" state, when it acts as either sender or relay. On the other hand, while on listening phase, it is said to be in its "off" state. We define the "on" period of a node (t_{on}) as the time it is engaged in either transmitting (T_{TX}) or forwarding (T_{fwd}) data. The time for which a node is in listening mode (T_{lst}) is considered as its "off" period (t_{off}). The duty cycle D of a node is given by

$$\mathrm{D} = t_{on} / (t_{on} + t_{off}) \qquad (2)$$

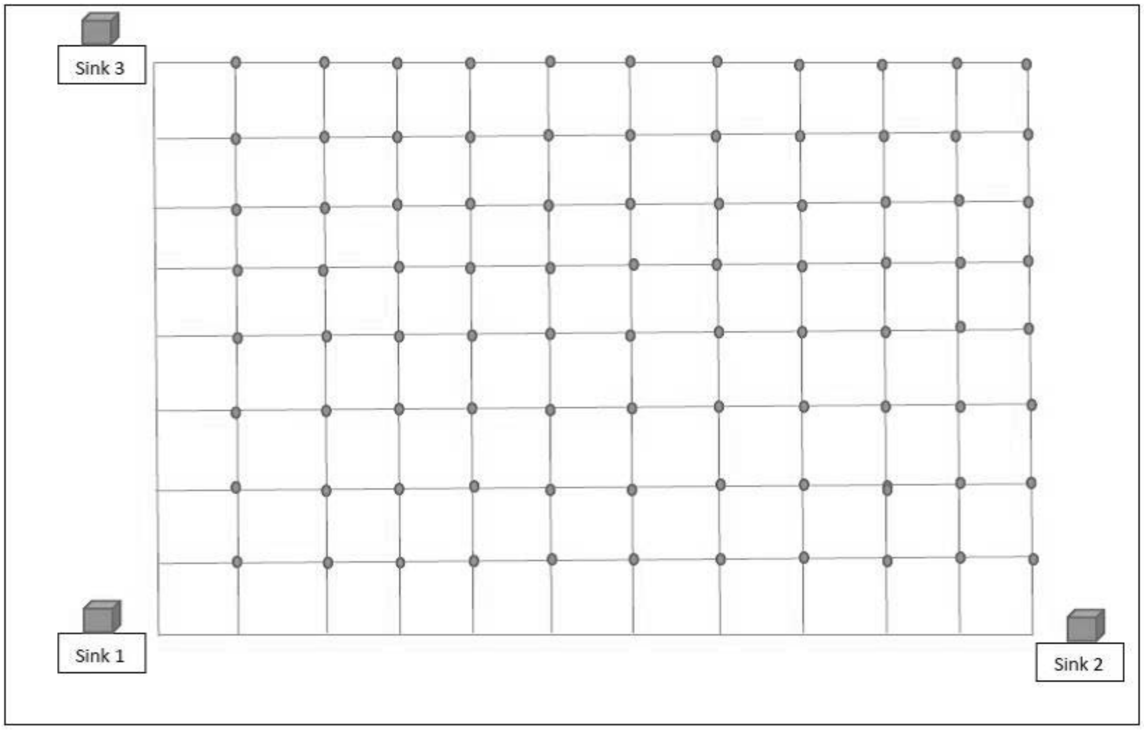

Figure 1. Sensors deployed over a rectangular agricultural land in grid fashion

From Min et al. [2001], we have taken the value of $E_{computing}$ as 117 nJ/bit. Similarly, $E_{sensing}$ is taken as 1.7 µJ/bit [Min and Chandrakasan [2001]]. $E_{listening}$ on the other hand is not a function of number of bits transmitted. Rather, it depends upon the number of seconds spent in listening mode and its value is taken as 570 µJ/s [Anastasi et al. [2004]].

The radio model is thus expressed as in Ghosh et al. [2016]

$$E_{TX} = m * 117 * 10^{-9} + m * 1.7 * 10^{-6} + (D * m * \varepsilon * d^{n}) \quad (3)$$
$$E_{forwarding} = \mathrm{D}(m * E + m * \varepsilon * d^{n}) \quad (4)$$
$$E_{listening} = (1 - D) * 570 * 10^{-6} \quad (5)$$

where
m = Packet size in number of bits
n= Path loss exponent
D = Duty cycle
E = 50 nJ/bit
$\varepsilon = 8.854 pJ/bit/m^2$
d = Inter-nodal distance

The values of E and ε are taken from Heinzelman et al. [2002]. ε stands for permittivity, and E is the minimum start-up energy required for any communication.
From KPS algorithm we find that more the number of 1-hop neighbors, greater would be the probability of selecting different neighbors for subsequent transmissions (equation 1) by a sender node. Ability to select different neighbors for different transmission or forwarding is in a way helpful in increasing network lifetime since no single node overworks. But increase in the number of neighbors with increase in transmission range (TXR) would have adverse effect on network lifetime because a sender would have higher probability of selecting a neighbor located at a distance, rather than nearer to itself. Considering the value of path loss exponent to be 3, increase in transmission distance beyond a certain point would take a toll on the lifetime of the network. This will be further clarified in the next section.

LF-KPS: In our further study of the KPS protocol, we found that it may exhibit looping at times. This is due to the fact that in KPS the next hop forwarder is chosen on the basis of its forwarding potential. The neighbor with the highest value of forwarding potential is selected as the next hop forwarder. In this process there remains a possibility that same node/s is/are selected for packet forwarding more than once in a single iteration. The concept of looping can be understood from Figure 2a. Suppose node 5 has to send a packet to node 1. According to the KPS protocol, node 5 will find the forwarding potential of all its neighbors, that is, node 1, node 2, node 3, node 4, node 6, node 7, node 8 and node 9.Suppose, the neighbor with the highest forwarding potential comes out to be node 6. The packet is transmitted to node 6. Now, the same procedure is followed by node 6 and eventually the packet is transmitted to node 8. Now, node 8 finds that out of all its neighbors, node 5 has the maximum value of κ and hence it transmits the packet back to node 5. This is where looping occurs. We propose in Loop Free-KPS (LF-KPS) scheme that once a loop is formed, it may be broken by using the Greedy forwarding technique. In the proposed LF-KPS algorithm this looping is removed by introducing a **composite id** for messages, comprising of the sender's id and the message id - $(sender_{id}, message_{id})$. Each message in its header would contain the id of the node from which it is generated and a unique id of the message as assigned by the sender.

With this arrangement, node 5 would now recognize that the message forwarded by 8 is actually the one generated by 5 earlier. Thus it would send back a control message, LOOP, to 8 with the composite id of the message for which looping took place. So, to avoid looping, node 8 now selects next hop forwarder using greedy forwarding (node 4 in this case). Finally the packet reaches its destination node 1 without any looping (Figure 2b).

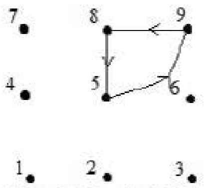

Figure 2a. Looping in KPS.

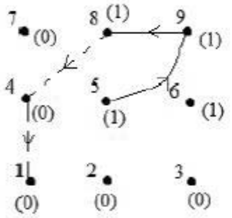

Figure 2b. Loop free KPS.

4. RESULTS

The simulations for the present work are done in MATLAB. This is because; all the other protocols with which we are comparing KPS and LF-KPS protocols have their codes in MATLAB only. Thus to have a common comparison platform, we chose to use MATLAB for simulation of our results. In this section, we have introduce the parameters neighbor density and node density, and discuss about their effect on lifetime enhancement of a WSN deployed for PA applications. We subdivide this section as follows: evaluation, introduction of novel parameters along with their importance and discussions.

4.1 Evaluation

Primarily, we started this work with KPS algorithm [Ghosh et al. [2016]] for data forwarding, aggregation and delivery to three sinks. Our reason for choosing KPS algorithm could be explained through Figure 3a from Ghosh et al. [2016]. It is seen that KPS algorithm outperforms Fermat point based variants of greedy forwarding (F-Greedy), residual energy based forwarding (F-Residual) and compass routing (F-Compass) for different values of AGFACT. Again, from Figure 3b we see that, lifetime of KPS is comparable with well-known protocols like LEACH [Heinzelman et al. [2000]], I-LEACH, Mod-LEACH [Mahmood et al. [2013]], SEP [Smaragdakis et al. [2004]], T-SEP, Z-SEP [Faisal et al. [2013]] and TEEN [Manjeshwar and Agrawal [2001]], and that of LF-KPS is much better as compared to all. The value of TXR considered was 100m and the nodes were considered to be deployed in grid fashion as in Ghosh et al. [2016] for results of Figure 3a. The parameters used for results of Figure 3b are given in Table I. The size of the grid is kept as 30m x 30m.In LEACH, I-LEACH, Mod-LEACH, SEP and TEEN, the value of path loss exponent (PLE) is taken as either 2 or 4 depending upon the distance between the communicating nodes. If the distance is less than an optimal distance, PLE value is set to 2 or else to 4. KPS and LF-KPS however maintained a uniform value for PLE as 3. For this work we have considered all the nodes in all the protocols as “ordinary” ones, i.e all the nodes deployed would have same initial energy. Moreover, the number of sinks considered in all the protocols was three – unlike traditional LEACH, TEEN, SEP and their variants, where a single sink is considered to be present.

Table I: Network parameters for grid deployment

Parameters	**Values**
Deployment mode	Grid
Grid size	30m x 30m
No. of sinks	3
Path loss exponent	3
Packet size	4000 bits
Initial energy of nodes	1 J
Node Density	0.0011
Source selection mode	Round Robin

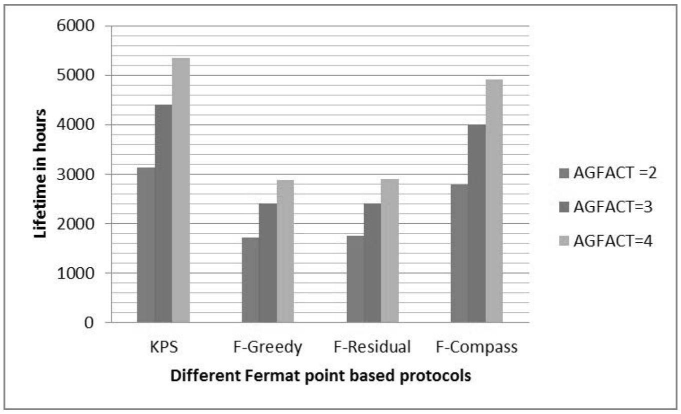

Figure 3a. Lifetime comparison of KPS algorithm with other Fermat point based algorithms

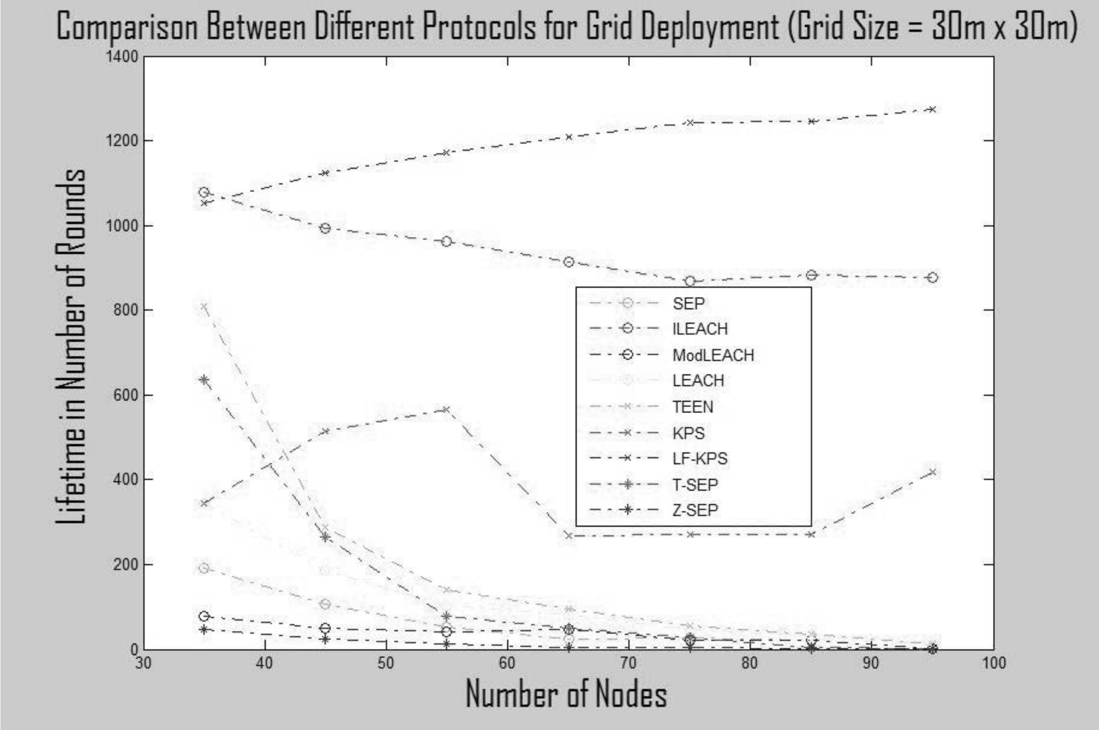

Figure 3b. Lifetime comparison of KPS and LF-KPS with other algorithms

4.2 Introduction to Novel parameters

In this section we would introduce some novel parameters that may be useful in regulating network lifetime of a WSN deployed for PA purpose.

4.2.1 *Neighbor Density.* In this paper we consider nodes to be capable of varying their transmission ranges (TXR) according to need. Now, with fixed grid size and variable TXR, we can control the Neighbor Density (ND) of a node. Neighbor density is defined as

$$ND = N_x * N_y \qquad (6)$$

where

N_x = ROUND (TXR/grid length along x axis)
N_y = ROUND (TXR/grid length along y axis)

KPS: From Figure 4 we see how selecting an optimum TXR and ND becomes helpful in maximizing lifetime of a multi-sink WSN with grid deployment. From Figure 4 we have tried to find out those optimum values for κ-forwarding, since that is the forwarding technique applied in KPS algorithm. Increase in TXR would increase the ND of a node. We can see that increasing the value of TXR till a certain point will increase the lifetime of the network due to the fact that number of 1-hop neighbors increases for each node. However, after that point the factor of transmission over a longer distance counterbalances the positive effect of having more number of neighbors.

The curves of Figure 4 fit best as 3rd degree polynomials. However, looking at the value of the leading polynomial (p1), it becomes evident that we can consider it to be zero for all practical purposes. For a 40m x 40m grid size, its value is as low as 0.0001 (Figure 4c). Thus, we may consider the nature of the graphs obtained in Figure 4 to be as parabolic. Thus lifetime (L) may be expressed in terms of TXR (T) with a standard equation of parabola in the following form

$$L = p_1 * T^2 + p_2 * T + p_3 \qquad (7)$$

One interesting thing to notice in all the three curves of Figure 4 is that maximum lifetime is reported at such a value of TXR that maintains a ND close to 9. The explanation of neighbor density as 9 is given later in this section under graphs of Figure 4. Network parameters for the simulation are as given in Table II.

Lifetime of the network is measured in number of completed cycles. After all the nodes in the network have transmitted at least once, we consider one transmission cycle to have completed. Lifetime of WSNs has been defined in different ways by researchers. We have considered the definition by Chang and Tassiulas [2000] for our work - a network is considered dead when the first node goes out of energy.

With grid size 30 m x 30 m and TXR as 100 meters, the neighbor density of the nodes becomes 9. From Fig 4(b) we can see that maximum lifetime of the network was recorded at around 85 meters TXR for both the protocols, for a particular set of network parameters. From Figures 4(a) and 4(c), we see that the maximum lifetime recorded for both the protocols is at 65 meters and 115 meters respectively. We can see that with change in grid size, value of TXR where maximum lifetime is recorded also changes.

Analyzing these three graphs of Figure 4 with help of equation number 6, we see that maximum lifetime would be recorded for TXR which maintains a Neighbor Density of 9, in all the three cases.

For the graph of Figure 4(a) we get, maximum lifetime at TXR = 65m. Grid length for this case is 20m along both x and y axes (see Table II). Therefore, the value of Nx and Ny for maximum lifetime would come as ROUND (65/20) = ROUND (3.25) = 3. Thus the neighbor density for which maximum lifetime is recorded is coming as 3 x 3 = 9 (see equation number 6). Similarly, for graph of Figure 4b, we see maximum lifetime to be recorded at TXR = 85m. The grid lengths in this case is 30m along both x and y axis. Thus, Nx = Ny = ROUND (85/30) =3. As a result, here also we get ND to be equal to 9, where maximum lifetime is reported. The exercise for graph of Figure 4c too shows that maximum lifetime is reported if we could keep ND to be equal to 9. Therefore, to get maximum lifetime we may optimize TXR to the point where it is possible to get a Neighbor Density of 9.

LF-KPS: After removal of looping from KPS, we carried out our simulations on the optimized protocol i.e. LF-KPS. We can see from figure 4d and 4e that the maximum value of

lifetime recorded for LF-KPS is at TXR values 30 meter and 50 meter for grid sizes 20 m x 20m and 30m x 30m respectively.
For Figure 4d, Nx = Ny = ROUND (30/20) = ROUND (1.5) = 2. Likewise for Figure 4e we get Nx = Ny = ROUND (50/30) = ROUND (1.67) = 2. Thus, from equation number 6, it becomes clear that LF-KPS records maximum lifetime at ND value of 4, which is a major improvement over the results of κ-forwarding. Network parameters taken for Figure 4d and Figure 4e are present in Table III.

Importance of Neighbor Density

Although theoretically it is possible to exploit this finding for any WSN application in order to maximize the network lifetime, it should be noted that many of the WSN applications may not support grid deployment of the nodes. However, fields where grid deployment may be carried out without any problem can choose proper grid size to enhance network lifetime. Grid sizes may be changed according to our will in order to accommodate for changing values of TXR. As a result, setting the value of neighbor density as specified in the previous sub section would not be a problem in grid deployment to maximize network lifetime.

Table II: Network parameters for studying effect of increased TXR on lifetime of three-sink WSN for KPS

Parameters	**Values**
Area	300 m x 300 m
Grid size	20 m x 20 m (4a), 30m x 30m (4b), and 40m x 40m (4c)
No. of nodes	225 (4a), 100 (4b), 49 (4c)
No. of sinks	3
Path loss exponent	3
Packet size	36 bytes
Initial energy of nodes	1 J
Node Density	0.0025(5a), 0.0011(5b) and 0.0005(5c)
Source selection mode	Round Robin

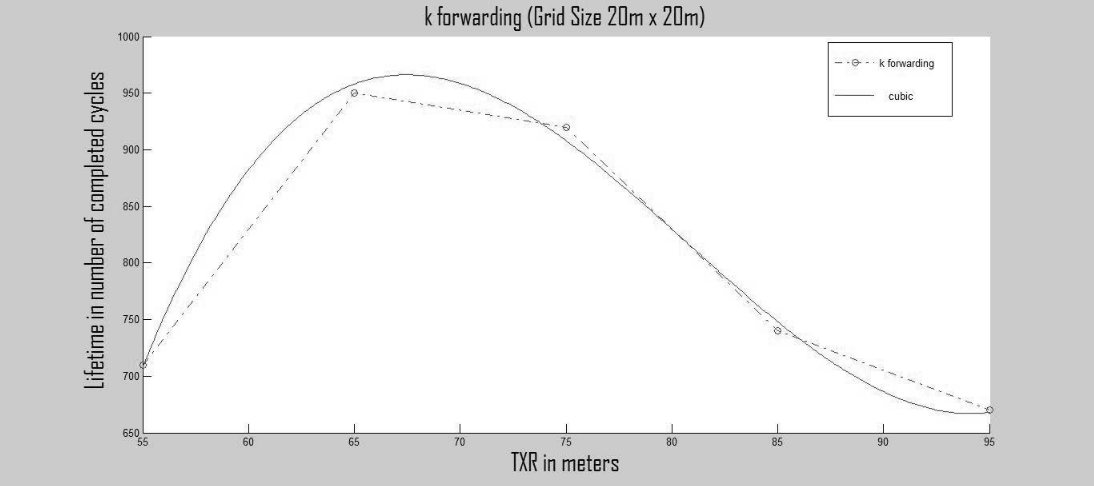

Figure 4a. Variation in lifetime of a 3-sink WSN for grid size 20m x 20m

Node Density: From Table II we get a new parameter - Node Density (NoD). We define it as

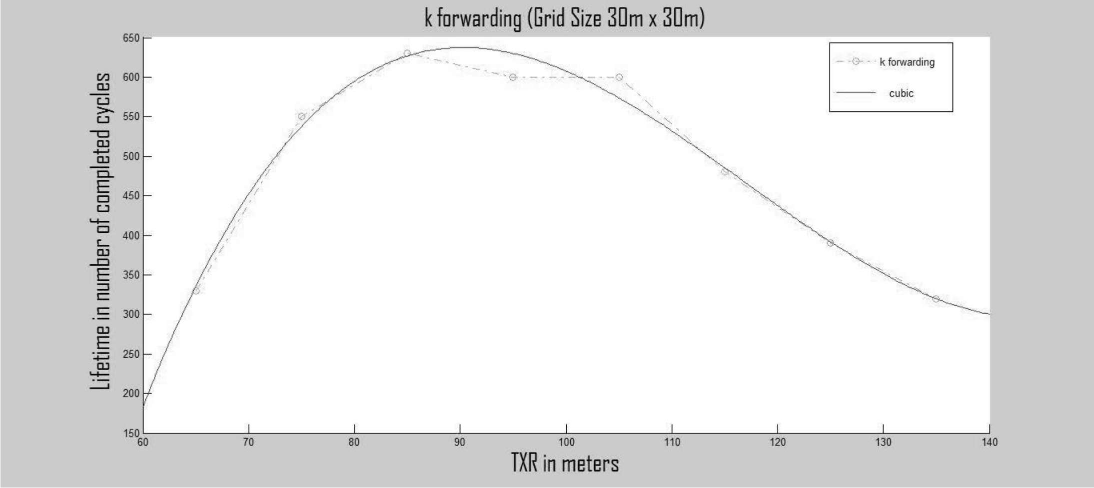

Figure 4b. Variation in lifetime of a 3-sink WSN for grid size 30m x 30m

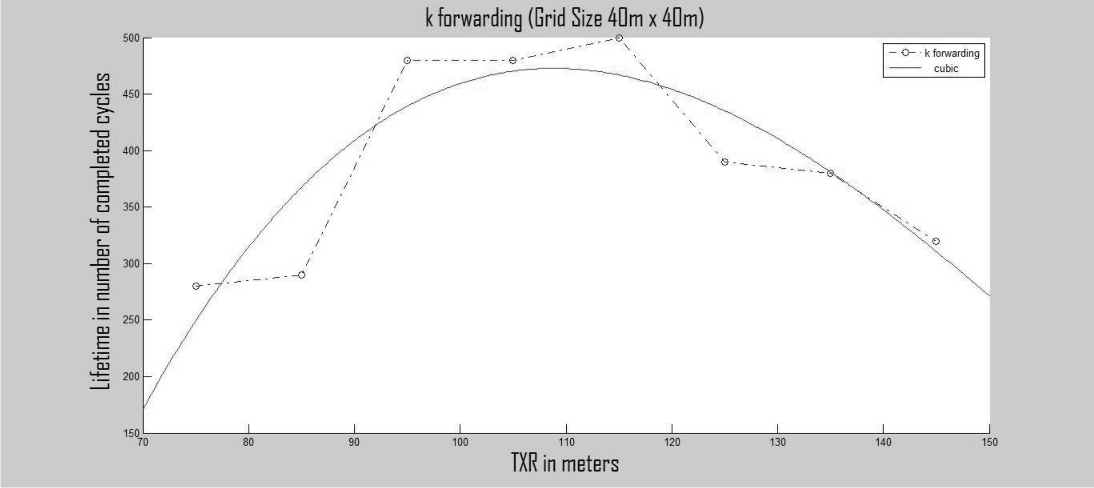

Figure 4c. Variation in lifetime of a 3-sink WSN for grid size 40m x 40m

Table III: Network parameters for studying effect of increased TXR on lifetime of three-sink WSN for LF-KPS

Parameters	**Values**
Area	200 m x 200 m (4d) and 300 m x 300 m (4e)
Grid size	20 m x 20 m (4d) and 30m x 30m (4e)
No. of nodes	225 (4d), 100 (4e)
Data Rate	38.4 kbps
No. of sinks	3
Path loss exponent	3
Packet size	4000 bits
Initial energy of nodes	1 J
Node Density	0.0025(4d) and 0.0011(4e)
Transmission mode	Round Robin

$$NodeDensity = \text{Number of nodes in sensor field/Total Area of Sensor field} \qquad (8)$$

Importance of Node Density

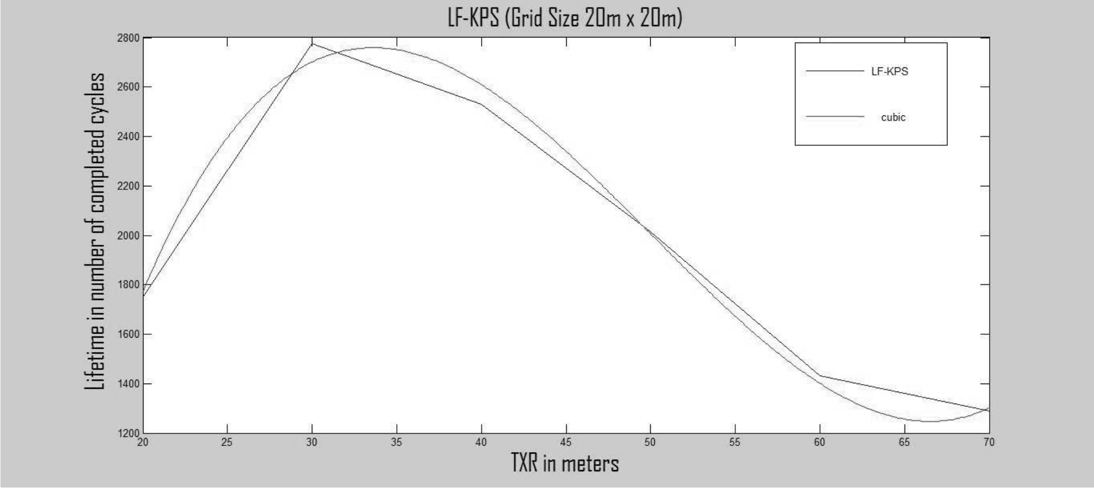

Figure 4d. Variation in lifetime of a 3-sink WSN for grid size 20m x 20m in LF-KPS

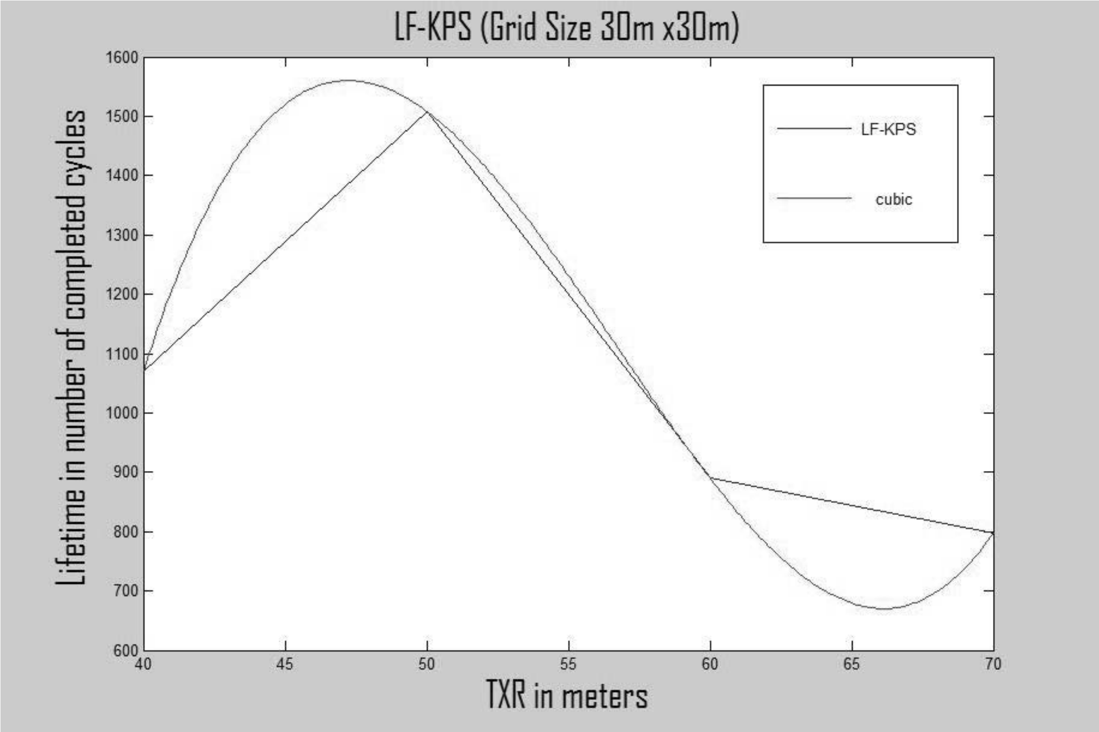

Figure 4e. Variation in lifetime of a 3-sink WSN for grid size 30m x 30m in LF-KPS

This parameter NoD is helpful for observing the variation in network lifetime with respect to TXR, when grid deployment cannot be ensured.

Effective Network Density. Since for random deployment, it is impossible to maintain a fixed value of ND throughout the network, we thus propose a composite parameter, **effective network density (END)** and compare network lifetime with respect to it. The term effective accounts for the fact that in spite of having both node density and neighbor density same for two different networks, it is observed that the network with more number of nodes among the two would actually report more lifetime. Thus, **effective density** of a network would be determined by combining the parameters node density, neighbor density and the number of nodes present in the network. END is defined as

$$END = NodeDensity * ND * \text{Total number of nodes} \tag{9}$$

Table IV: Different values of node and neighbor density over an area of 150m x 300 m

Grid Size	Number of Nodes	Node Density	Effective Network Density	Neighbor Density
30m x 15m	100	0.0022	18	3.96
15m x 15m	200	0.0044	36	31.68
10m x 10m	450	0.01	100	450

Importance of END

Applications where grid deployment is impossible, network lifetime may not be regulated/ maximized through neighbor density. In case of random node deployment, one may think of using END as the parameter to regulate network lifetime.

4.3 CUMULATIVE DELAY

However, an increase in network lifetime with an increased END comes at the cost of an increased However, an increase in network lifetime with an increased END comes at the cost of an increased cumulative delay in the network. Cumulative delay is defined as the summation of total delay incurred at every node starting from the time of network installation till the time when the first node is fully depleted of energy. in the network. Cumulative delay is defined as the summation of total delay incurred at every node starting from the time of network installation till the time when the first node is fully depleted of energy.

$$\text{Cumulative Delay} = \Sigma_{i=1}^{i=n}\ \Sigma_{t=0}^{t=l}\ \sigma_{it} \tag{10}$$

where

σ_{it} = Delay at node i during time t
n = Number of nodes in the network
l = Time when the first node of the network goes out of energy

Cumulative delay would increase with increase in sampling period and AGFACT (Fig 5). More the sampling period and AGFACT, longer a packet has to wait at the FN to get transmitted and this increases the delay. This is because, a node may have transmitted its first packet to the FN. Now FN would aggregate other packets with it before forwarding it further to the sinks. More the value of AGFACT, more is the time FN needs to wait for all the packets to arrive for doing the required aggregation. Again, packet arrival in FN (or any other node for that matter) is dependent upon the sampling period, that is, the time interval between two consecutive data collection events by a node. Greater the sampling period, larger is the time a packet needs to wait in FN for arrival of other packets, before they all can be aggregated. Since cumulative delay is a measure of interval between end to end packet transmissions, a high cumulative delay can affect the performance of a given application.

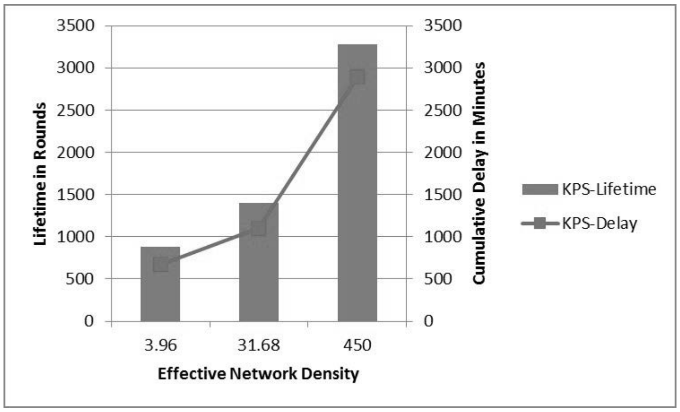

Figure 5. Increase in lifetime and cumulative delay with increase in node density and neighbor density

IMPORTANCE of CUMULATIVE DELAY
In case the application is too much delay sensitive, the value of AGFACT then may be chosen such that the induced cumulative delay remains within permissible limits.

4.4 DISCUSSIONS

From section 4.1 we can see that our proposed scheme outperforms protocols like LEACH, Mod-LEACH, I-LEACH, TEEN and SEP by a considerable margin for grid deployment. In sensor nodes deployment for applications like Precision Agriculture and Intrusion Detection; grid deployment pattern is followed almost everywhere. Hence, the present scheme may be chosen to ensure a longer lifetime for the network deployed for such domains. A longer lifetime of WSN deployed would amortize the running cost of the setup.
In section 4.2 we introduced novel parameters like ND, END and cumulative delay. We could see that by maintaining the value of ND as 4 in case of LF-KPS, we can maximize network lifetime for grid deployment.
For a sensor field with fixed TXR, if it is inconvenient to change the grid size (because that implies redeployment of the network) to get a neighbor density equal to 4; one may think of deploying extra nodes in the network to increase the END. This in turn would increase network lifetime. Judicious selection of cumulative delay is required by considering the nature of application chosen.

Cumulative delay is a function of the end to end delay in the network for packet forwarding. It is more for higher values of END. Hence, one must keep an eye on the level of delay sensitivity of the network chosen network. It is observed from the work in Ojha et al. [2015] that an architecture similar to the one presented in the current paper, could be used for measuring various multipurpose farm parameters, e.g., soil moisture, ambient temperature, relative humidity, ambient light, ambient temperature etc. in fact presence of multiple sinks will enhance the activities since each sink may be entrusted to deal with different sets of parameters. However, the sinks may be general purpose also and deal with all parameters. The lifetime of the network can be regulated as described in this paper and this will immensely help farmers and agriculturists.

5. CONCLUSION

The proposed model may be used for applications where grid deployment would come as a natural choice. For example, precision agriculture. Here we have introduced two parameters for network lifetime regulation – neighbor density and effective network density and observed the behavior of lifetime with respect to these and other factors.

The advantage of grid deployment may be harnessed to use parameters like neighbor density and node density and regulate lifetime of the network. A neighbor density of 4 in case of LF-KPS can ensure maximum lifetime in multi-sink WSNs. However, maintaining the said neighbor density for all nodes in the network is possible when one can guarantee a uniform spatial resolution of the nodes. This again is possible with grid deployment. Random deployment of nodes on the other hand fails to ensure uniform neighbor density for all nodes. However, one may think of using effective network density as the regulating parameter for network lifetime in those cases. Needless to say, END may well work as regulating parameter for network lifetime in case of grid deployment also. Increasing network lifetime with an increase in END would come at the cost of greater cumulative delay. However, cumulative delay may be reduced by reducing the sampling period. Reduction in AGFACT may not always be recommendable as data aggregation reduces the number of packet transmissions and thereby increases network lifetime.
Another tradeoff which may be carried out is between delay and energy consumption in a network.

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