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Topology Control for Harvesting Enabled Wireless Sensor Networks: A Design Approach

Hassaan Khaliq Qureshi · **Adnan Iqbal** ·
Waqar Asif

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Abstract While there has been a lot of research on energy efficient topology control protocols destined for different applications, topology control has never been explored in the presence of harvesting enabled sensors. Largely, researchers in this domain have considered a fixed battery design. We argue that arrival of harvesting enabled sensors necessitates rethink of topology control. The objective of topology control in this context should not be to minimize the spent energy and maintain a reduced topology, but to maximize fault tolerance in the network and increase the sensing coverage region. In this work, we first describe a taxonomy of existing topology control schemes and analyze the impact of reduced topology over fault tolerance and sensing coverage. We then describe the necessity of new design parameters in the presence of harvest-able ambient energy. We also outline guiding principles for designing a harvesting enabled topology control scheme. To cater for whether such a scheme is feasible or not, an insight is also provided onto the solar energy availability from solar radiations for near perpetual operation – as an example of available ambient energy. Based on the insight gained from the solar radiations availability, we explain why new design parameters are required for performance measurement of harvesting enabled sensors. The mathematical and empirical findings reveal that the topology control strategies, which do not take into account harvesting opportunity, are unable to provide better results in terms of fault tolerance and sensing coverage.

H. Qureshi · W. Asif
School of Electrical Engineering & Computer Science (SEECS),
National University of Sciences & Technology (NUST), Islamabad, Pakistan.
E-mail: (hassaan.khaliq,09mscsewasif)@seecs.edu.pk

A. Iqbal
NAMAL College, Mianwali, Pakistan.
E-mail: adnan.iqbal@namal.edu.pk

W. Asif
School of Engineering and Mathematical Sciences, City University, London, UK.
E-mail: Waqar.Asif.1@city.ac.uk

1 Introduction

The advancement in harvesting enabled technologies has led to the design of self-sustained devices, which collects a part, or all of the energy from the environment and transfer it to nodes with scarce resources [8][22][10][37][42]. Due to this reason, existing protocols are being modified to consider available ambient energy as an alternative source [20][13]. The wireless sensor networks (WSNs) are now becoming harvesting enabled and therefore present new challenges and design issues that are different from conventional battery powered networks/systems. The energy harvesting potentially offers near perpetual operation, but might not guarantee it sometimes due to the unavailability of harvesting opportunity. While such techniques have been studied at various levels, the design of harvesting aware topology control solutions needs to account for the potential changes in the traditional methodology of topology control.

Topology control is a twofold process in which a reduced topology is constructed for energy conservation of nodes, while also maintaining it by shifting the roles of nodes from active to sleeping state and vice versa. In this context, several algorithms and protocols have been proposed to increase the network lifetime, which is achieved by reducing the unnecessary communication between the nodes in the network during topology construction and maintenance [34][40][15]. However, the increase in the lifetime is at the cost of reducing the fault tolerance in the network. In the context of harvesting enabled devices, this traditional methodology of conserving the energy becomes less important; therefore, new design parameters such as fault tolerance/network reliability, network perpetual operation, and sensing coverage region should be accounted for the re-design of a topology control process [39][7].

In this paper, solar irradiance harvesting is considered as a viable alternative to fixed batteries. For this purpose, an insight from the global irradiance data is taken to analyze the photovoltaic module size requirements in different parts of the world for a solar energy harvesting sensor. Since the diurnal behavior and intensity of solar radiation varies significantly, therefore, the topology control for harvesting enabled sensor network should be adaptive to these variations. To validate the findings on the variations, the storage capacity of the solar radiations in the months with less harvesting opportunity is analyzed. Similarly, the performance metrics in the context of harvesting enabled sensors are evaluated followed by the proposed modifications in the design of topology control. The results reveal that the discontinuous radiation availability should be taken into account, and parameters such as fault tolerance, sensing coverage region gets improved in the presence of sensors with more harvesting opportunities.

The rest of this paper is organized as follows. Section II summarizes the taxonomy of topology control schemes. The empirical and mathematical results on certain topological structures are analyzed in Section III. Section IV provides an analysis on the solar radiation availability from the global radiation dataset with guidelines on the re-design of topology control in section V. The salient findings of the paper are summarized in Section VI.

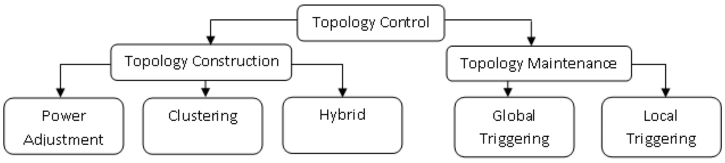

Fig. 1 Taxonomy of topology control mechanism.

2 Taxonomy of Current Topology Control Schemes

Topology control protocols that aim for energy conservation have been extensively proposed [12][16][38][20][24]. In this section, we describe a high level taxonomy of topology control process for taking harvesting opportunities into consideration while designing or developing an algorithm. We shall have a brief discussion on the generalized topology control schemes by breaking the taxonomy. Later, some of energy provisioning schemes for MAC protocols are also briefly explained. Topology control is based on two design considerations; topology construction and topology maintenance as shown in Figure 1.

2.1 Topology Construction

In the topology construction, a reduced topology is build once the sensor nodes are deployed and activated. It is also ensured that the new topology built will result in better energy conservation at the same time making sure that the network remains connected. We categorize our discussion into three major subsections in order to clearly identify characteristics of each scheme.

2.1.1 Power Adjustment

Power adjustment approaches conserve energy by reducing or adjusting the transmission power of nodes. The nodes work in a collaborative manner to find the minimum possible transmission range required for connectivity and hence transmit at the reduced power level. Some of the prominent power adjustment approaches are described in this subsection.

The COMPOW proposed in [30] is one of the first protocols to be implemented on a real wireless test bed. The COMPOW conserves energy by reducing the transmission power to such a level, which is sufficient to maintain network connectivity. The authors argue that this in return provides many advantages such as improvement in the traffic carrying capacity, energy consumption and contention resolution at the MAC layer. The use of reducing the power level also results in the use of bidirectional links, which on the other hand provides many advantages at the MAC layer. The protocol use parallel modularity at the routing layer to achieve asynchronous and distributed operations.

The authors in [35] have proposed Minimum Energy Communication Network (MECN) algorithm which minimizes the energy involved in transmission of packets in a WSN. By using positioning system, a topology consisting of low energy paths is constructed for transmitting information from any node to a sink node. The algorithm works in two phases where a node in the first phase identifies set of neighbors with which it can communicate by spending minimum packet transmission energy. In the second phase, Bellman-Ford shortest path algorithm is used to determine the minimum energy path to the sink node. The minimum power consumption required to send a packet to the sink is broadcasted in case of being used as relay towards the sink node. When a node u receives the cost information from a neighbor node v, it calculates the minimum cost of the path to the sink relayed through v as:

$$Cost(u,v) = Cost(v) + d(u,v)^n + \beta. \tag{1}$$

where, $d(u,v)$ is the Euclidean distance between the nodes u and v, n is the path loss exponent and β is the power consumed at a receiver acting as a relay node. Similarly, the authors in [25] have proposed Small Minimum Energy Communication Network (SMECN) algorithm, which aims to construct a simpler, faster and more energy efficient network than the one generated in MECN [35]. As SMECN is a variant of MECN, therefore, it uses the same assumptions and energy model but the objective is to generate a subgraph G which is smaller than the subgraph G in MECN. The SMECN also uses a two phase approach but unlike MECN, the nodes once considered as neighbors are never removed from the neighbor set and they are all included in the enclosure graph. A more energy efficient version of the algorithm based on SMECN have also been proposed by the same authors in [26], which construct a minimum energy graph under dynamic topology changes.

2.1.2 Clustering

The clustering approaches conserve energy by critically selecting nodes, which works as a backbone for all the other nodes in the network. To improve energy efficiency, the nodes not in the backbone switch-off their radios move into a sleep mode which consumes less energy. The authors in [6] have studied many clustering algorithms categorized according to cluster attributes, cluster head capabilities and clustering process. However, the differentiation in context to the topology control process in not highlighted.

The authors in [45] proposed a Power Aware Connected Dominating Set (PACDS) protocol which uses a marking and pruning rule to construct a Connected Dominating Set (CDS). The authors claim that PACDS requires only one round of message exchange for executing both the rules. Due to this reason, PACDS has less message and time complexity. However, the protocol does not cater any dynamic change in the topology and is only suitable for static and low mobility networks.

The authors of [47] have proposed an Energy-Efficient CDS (EECDS) protocol that computes a sub-optimal CDS in an arbitrary connected graph by using a coloring scheme. EECDS uses two phase strategy to find a CDS. Initially in the first phase, all nodes are in white state and at end either becomes black or gray. A node elects itself as a cluster-head and then all its neighbors are marked as covered in order to find a Maximal Independent Set (MIS). The second phase identifies the gateway nodes for MIS and connects the MIS to build the CDS. All the covered nodes except the cluster-heads compete to become gateways to form a CDS. In EECDS, nodes maintain the cluster-head role by gathering neighbor information which allows uniform distribution of energy resources. Similarly, authors in [44] have proposed CDS-Rule K, protocol, which also uses marking and pruning rules to exchange the neighbor's lists among a set of nodes. A node remains marked if there is at least one pair of unconnected neighbors and un-marks itself if it determines that all of its neighbors are covered with higher priority. The node's higher priority is indicated by its level in the tree.

2.1.3 Hybrid

In order to conserve energy, hybrid approaches are used by integrating the clustering approach with either power mode or power adjustment approaches. Low Energy Adaptive Clustering Hierarchy (LEACH) is a localized algorithm that allows each node to gather information from its neighbors based on the received signal strength [17]. It uses the cluster head nodes as routers to the base-station and the role of the cluster heads is rotated periodically among the nodes in the network. In order to evenly distribute the load among cluster heads, the rotation is performed by getting each node to choose a random number T between 0 and 1. A node becomes a cluster head for the current rotation round if the number is less than the following threshold:

$$T(i) = \begin{cases} \frac{p}{1-p^*(rmod\frac{1}{p})} & \text{if } i \in G, \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

Where p is the desired percentage of cluster head nodes in the sensor population, r is the current round number, and G is the set of nodes that have not been cluster heads in the last $1/p$ rounds. The LEACH has a scalability issue which is addressed by Hybrid Energy-Efficient Distributed Clustering (HEED) [46]. HEED is a distributed clustering scheme which considers a hybrid of energy and communication cost when selecting cluster heads. Unlike LEACH, it does not select cell-head nodes randomly. Only sensors that have a high residual energy can become cell-head nodes.

The A3 algorithm [43] combines the clustering approach with the power mode approach to allow idle non-connected dominating set (CDS) nodes to switch to sleep mode, thus conserving energy consumption and simplifying the switching mode operation. It uses different type of short and long messages to construct a CDS, which works on behalf of rest of the nodes in the network. Similarly, the authors in [34] propose an A1 algorithm which provides advantage over A3 in terms of message complexity. The A1 constructs the CDS by using less number of messages and thus providing better energy efficiency. Moreover, the two approaches are also combined by many authors to achieve the reliability in addition to energy efficiency [12] [6] [32] [41]. Most of the algorithms explained in the previous subsections consider topology control as a single phase construction process, but not explain how to maintain the constructed topology. Due to the fact, some of the topology maintenance schemes which can be used with topology construction protocols are explained in the next subsection.

2.2 Topology Maintenance

The topology maintenance changes the topology of the network and the state of the nodes, rotating the role of nodes between an active and sleep state. The main idea behind the application of these techniques is to keep as few active nodes as attainable for increasing network lifetime. Based on the classification, some of the topology maintenance schemes are explained in the next subsections.

2.2.1 Global Triggering

The focus of recent research has shifted to local schemes, but global techniques continue to be employed in WSNs. The local schemes are divided on the basis of topologies, which are built based on time triggering or energy triggering criterion.

In [23], authors present Static Global Topology Rotation (SGTRot) which is a static approach for rebuilding topologies. The SGTRot builds multiple reduced topologies based on a virtual network interface (VNI) during topology construction, which are rotated when the running topology needs to be changed. The sink node is informed whenever a trigger is initiated in any of the nodes, which allows rotation of the topology. Dynamic Global Topology Recreation (DGTRec) is perhaps the most frequently employed topology maintenance scheme which does not require any pre-calculated information or Virtual network interface [28]. The sink node schedules the recreation of the topology once the triggering criterion is reached.

The dynamic topology maintenance is defined as the self-healing and recovery capability to reconstruct topology when suffering from failures. At the cost of more energy consumption, Dynamic topology maintenance has the advantage of having more and better information about the network. The cluster-based algorithm described in LEACH [17] uses a global scheme for controlling/maintaining the topology of clusters, which executes in rounds, periodically. It is worth nothing that in the presence of nodes with harvested energy, the dynamic topology maintenance will also be modified.

Hybrid Global Topology Recreation and Rotation (HGTRecRot) scheme combines the best of both static and dynamic schemes and hence works statically and dynamically [28]. Like a static protocol, HGTRecRot creates several VNIs at the start of topology construction which can be used upon requirement. However, once the calculated VNIs cannot be applied for example when the sink node detects it has been isolated from the network, HGTRecRot invoke dynamic topology maintenance. The sink node then transmits a Reset message to all its neighbors which is forwarded to rest of the nodes in the network. By sending a Reset message the sink node invokes the topology construction mechanism to update the current VNI as in DGTRec. After resetting the current VNI, the sink node still remains isolated; it will eliminate the current VNI from the list of available ones and will rotate to the next VNI. If there are no more VNIs available, then the sink determines that the network has reached its limit.

2.2.2 Local Triggering

Although centralized or global approaches are applicable in most of the scenarios and are easier to develop, these approaches have a single point of failure and may result in increased overhead particularly when network size increases and information has to transverse several hops. Therefore, recent research has been focused on developing local triggered schemes which do not involve all the nodes in the network. The local topology maintenance schemes involve a limited number of nodes and guarantee efficient energy consumption.

The ASCENT Adaptive Self-Configuring Sensor Network Topology or ASCENT [9] is a distributed protocol capable of self-reconfiguration. In ASCENT, nodes monitor their operating condition locally and make a decision whether or not to participate in a routing process. The nodes maintain two states namely active and passive and switch between them to become part of the routing backbone. For instance, when there is a higher rate of packet loss, the passive nodes are turned active in order to preserve connectivity. The ASCENT is a self-reconfigurable and adaptive to applications with dynamic events. It is worth mentioning that ASCENT takes topology control as a single process and does not separates the maintenance part. Similarly, the DL-DSR Dynamic Local DSR or DL-DSR is a local energy based scheme which follows the Dynamic Source Routing (DSR) [21] protocol for wireless networks. The DL-DSR follows CDS based approach to find substitute for a node whose energy has depleted to a specific level by sending wakeup and route request messages to the neighboring nodes. The topology is recreated locally, without the need of involving the sink node. The benefit of this protocol is that it has small message overhead as compared to global techniques.

The authors in [36] propose Efficient Topology Maintenance Scheme for Wireless Sensor Networks (EETMS) which is a local failure based scheme. The EETMS recreates topologies by controlling the transmission power of the neighboring nodes of the failed node, such that the network remains connected. There are two steps proposed in [36] that achieve this goal. The first step is to connect all immediate neighbors of faulty node by adjusting the transmission power of all immediate nodes with the shortest link. In the second step, a connected local network with the minimal possible power (the sum of the path lengths) using a Breadth First Search (BFS) mechanism is attained.

Specific to the topology control for harvesting enabled sensors have not yet been explored. However, other efforts such as in [19] evaluate conventional MAC protocols, such as the classical TDMA and variants of ALOHA under packet deliverability metric, assuming again out-of-band RF transfer for harvesting enabled sensors. Similarly, authors in [31] propose an RF-MAC protocol that optimizes energy delivery to the desirous sensor node on request. The authors in [22] have made several research efforts regarding energy management in environmentally powered sensor networks. Spatially distributed nodes might not have equal harvesting opportunities so the node adapts dynamic duty cycling according to the availability of the harvested energy. Similarly, the author in [33] use mobile nodes called energy producers to move freely around the network to charge themselves with sufficient solar energy, which is later used to charge energy deficient static nodes. Meanwhile efforts have been made to improve the output efficiency of solar cells. Based on the ambient sunlight intensity, the system dynamically adjusts its load to produce the maximum power available in order to achieve better system performance [11].

As topology reduction causes a decrease in fault tolerance and sensing coverage, therefore different topological structures are analyzed in the next section.

3 Topology Control Analysis

This section is divided in two subsections. In the first subsection, fault tolerant topological structures are discussed followed by the discussion on the sensing coverage opportunities for such structures in the second subsection.

3.1 Analysis of Topology Reduction and Fault Tolerance

Many critical WSN applications require a high degree of resilience against errors and attacks. The topological structure plays an important role in providing the fault tolerance in the network. It is due to the reason that the redundant network topology demonstrates a robust behavior after a random failure of a node or a link. However, in order to achieve the energy efficiency, the fault tolerance in the network becomes compromised. Although there are methodologies to introduce the data reliability [12][27], but fault tolerance in the context of harvesting enabled sensors have never been addressed.

Fault tolerance is measured by the impact of arbitrary failures on the characteristic shortest path length in a network. This is an appropriate measure for fault tolerance since a high impact on the path length subsequently requires more resources for communication. The topological structures with less characteristic path length and high clustering coefficient demonstrates a more resilient network in terms of sudden link failures and targeted attacks. However, such topological structures can only be possible with harvesting enabled sensors since redundant communication links can be used.

The characteristic path length is defined as the mean of the shortest path lengths between all pair of vertices. It is given by:

$$l = \frac{1}{n(n-1)} \sum_{i,j} d(v_i, v_j,) \tag{3}$$

Here n represents the number of nodes/vertices in a network and d is the distance between nodes i and j for all pair of active nodes in the network. On the other hand, packet forwarding probability (P_f) is defined as, the probability that a packet will be successfully delivered to the next hop in the path length between the source and the destination node. The packet forwarding probability is the product between the probability of not having a collision at the MAC layer P_c and the probability that a packet is not lost due to channel errors (P_e), and is given by:

$$P_f = P_c P_e \tag{4}$$

From the above two equations, the packet delivery reliability is deduced as:

$$R(P_f, l) = P_f^l \tag{5}$$

The possibility that the packet will be delivered towards the destination is dependent on the path length. Therefore, the less the characteristic path length, the more the packet delivery reliability. On the other hand, the clustering coefficient measures the degree of how strongly the neighbors of a node are clustered. In undirected networks, the clustering coefficient C_n of a node n is defined as:

$$C_n = 2e_n/(k_n(k_n - 1)) \tag{6}$$

where k_n is the number of neighbors of n and e_n is the number of connected pairs between all neighbors of n. The clustering coefficient is a ratio N/M, where N is the number of edges between the neighbors of n, and M is the maximum number of edges that could possibly exist between the neighbors of n. The average clustering coefficient distribution gives the average of the clustering coefficients for all nodes n with k neighbors for $k = 2, \ldots$. It is known that a high C_n leads to a more resilient network. In order to demonstrate the resilience, topologies of WSNs with different clustering coefficients were measured to judge the impact of sudden link failures on the path length. The most critical factor in judging the WSN topology is the limited transmission range that restricts adding the links between the devices, which are not in the transmission range of each other. Besides this restriction, using the maximum transmission range impact the energy consumption and therefore effects the overall network capacity [14]. Therefore, in order to analyze the clustering coefficient and characteristic path length in a WSN, certain dedicated links were removed to maintain a certain degree of connectivity from the sample network/original topology for verification as shown in Figure 2.

The communication graph for the WSN is constructed such that $V \in R^2$ is a set of nodes in the 2-dimensional space with side length l. The links E of the symmetric Euclidean graph $G = (V, E)$ fulfill the condition that for any pair $u, v \in V$ of nodes, $dist(u, v) \leq r \Longrightarrow u, v \in E$ and $dist(u, v) > r \Longrightarrow u, v \notin E$. The nodes are considered as being stationary with same transmission radius r, with nodes being deployed following a random process. Similarly, the neighborhood of a node v is formally defined as a sub-graph S that consists of all nodes adjacent to v. The 2-neighborhood or 2-hop neighbors of a node v is then the sub-graph that consists of all nodes adjacent to any of the nodes in S, but not including the nodes of S. It can also be generalized for k-neighborhood or k-hop neighbors with increase in k often implies, an exponential increase of the message complexity. In order to validate the results, Network Analyzer tool available in Cytoscape [1] and MATLAB [2] were used for experimentation. The degree of each node was tuned in a such a way that it produces a graph with desired degree of connectivity.

The network shown in a) is more tolerant to faults with high network density and more average number neighbors. Similarly, for the sake of demonstration, link have been removed and therefore the average node degree is changed and it shows that the network shown in b) is less fault tolerant as shown in Figure 2 and Table 1. It is due to the reason that network a) have high clustering coefficient and low characteristic

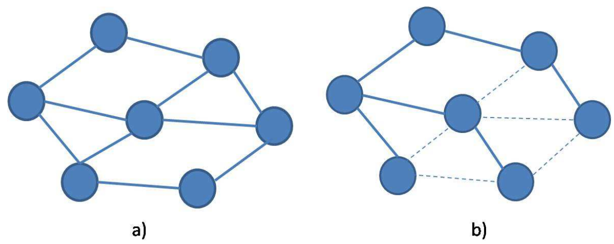

Fig. 2 Network example with a) Original Topology b) Reduced topology with link removal.

Table 1 Performance comparison of original and reduced topology for the sample network.

Name	Original Topology	Reduced Topology
Clustering Coefficient	0.23	0.00
Characteristic Path Length	1.57	2.38
Avg. No. of Neighbors	2.85	1.71
Network Density	0.47	0.28

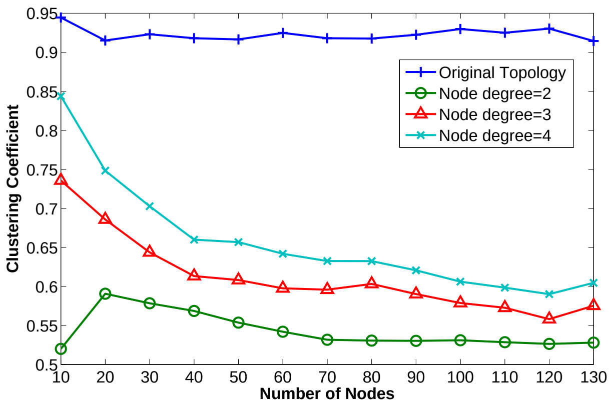

Fig. 3 Comparison of change in Clustering Coefficient against the increase in number of nodes.

path length. On the other hand, topological structures which try to improve energy efficiency with link removal – building a backbone tree – are unable to provide fault tolerance and better packet delivery reliability. However, depending on the harvesting opportunity available to the sensor motes, the increase in the number of redundant links can further increase the packet delivery reliability and fault tolerance.

To validate the results in Table 1, a network on an area of $350 \times 350m^2$ was deployed, with a transmission radius (T_r) upto $100m^2$. The number of nodes is varied from $10 - 130$ nodes. To analyze the effect of change in node degree on the performance of the network, the connectivity of the network was varied by changing the node degree from $2 - 4$ nodes. It was also assumed that the Original Topology have more number of neighbors per node i.e. node connectivity exceeds 4 nodes. For each

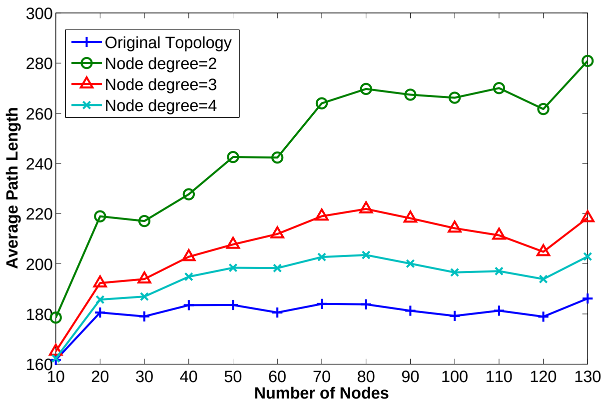

Fig. 4 Comparison of change in Average Path Length against the increase in number of nodes.

network the shortest path routes are formed using the Dijkstra's algorithm and then the parameters are monitored. Figure 3 shows the effect of increase in number of nodes on the clustering coefficient. The results demonstrate that the Original Topology has more node degree, providing maximum node connectivity and resulting in the highest clustering coefficient. It is due to the reason that the network formed is dense and therefore nodes are closely clustered. Due to this reason, it allows the possibilities of having more triplets with varying node density and therefore increasing the clustering coefficient. It can be concluded that the clustering coefficient of the Original Topology changes due to the higher node degree i.e. nodes tend to cluster together for sparse and the dense networks. On the other hand, the decrease in the overall node degree, results in the decrease in clustering coefficient. Similarly, the clustering coefficient gradually decreases with the change in the node density due to the fact that the same node degree is maintained. Therefore, it can be concluded that the networks with high node degree have high clustering coefficient and is more tolerant to faults.

Figure 4 shows the effect of increasing number of nodes against the change in average path length. It depicts that, the Original Topology having high node degree, provides maximum alternate paths to nodes for forming shortest path routes and resulting in low average path length. It is worth mentioning that the hop count was taken as the value of the transmission range for the Y-axis shown in Figure 4. On the other hand, as the node degree gradually decreases, the average path length of the network increases, resulting in the maximum average path length for the network having a node degree of 2. The increase in possibilities of forming shortest path routes leads to lower values of average path length with the increase in number of nodes. Therefore, a network having more connections allows many redundant paths towards the sink node, resulting in better packet forwarding probability.

3.2 Analysis of Topology Reduction and Sensing Coverage

The sensing coverage region of a node not only depends on sensing abilities of a sensor, but also dependent on the characteristics of an event and the sensor node. For the sake of simplicity, it is assumed that both the sensor and the event are static to each other. In this regard, the sensing probability (P_s) of a sensor node to detect an object decreases with an increase in the distance between the sensor node and the object. By using the log normal shadow fading model, we can express the path loss as:

$$L_p = \beta_0 - 10n\log\left(\frac{d}{d_0}\right) + X_\sigma \tag{7}$$

where X_σ is zero mean Gaussian random variable with standard deviation σ. Similarly, n is called the path loss exponent which varies between 2 and 5 depending on the environment while β_0 represents the loss due to antenna parameters and signal wavelength at a reference distance d_0.

Each sensor has a receive threshold α that describes the minimum signal strength that can be correctly decoded at the sensor. The probability that the received signal level at a sensor will be greater than the receive threshold, α, is given by:

$$P_s\left[P_s(d) > \alpha\right] = Q[\frac{\alpha - P_s(d)}{\sigma}] \tag{8}$$

The above equation requires Q-function to compute the probability involving the Gaussian process. The Q-function is defined as:

$$Q(r) = \frac{1}{\sqrt{2\pi}}\int_s^\infty \exp(-\frac{x^2}{2})dx \tag{9}$$

Where,

$$Q(r) = 1 - Q(-r) \tag{10}$$

The probability of receiving a signal above the receive threshold value, α, at a given distance can be calculated for a given transmit power using the above equations. It is eminent that as the distance of an object from the sensor increases, the sensing probability decreases exponentially.

The sensing probabilities with distance can be represented by concentric circles drawn at an increasing constant distance from the sensor node. The circles represent the probability of correctly receiving a signal with strength above receiving threshold at distance equal to circle radius. Similarly, for a deployed network topology, an object can be covered by more than one sensor node. Therefore, the individual detection probabilities of all sensors detecting the event occurring at that point can be measured to compute the cumulative sensing probability. The overall sensing probability (P_s) is given by:

$$P_s = 1 - \prod_{i=1}^{n}(1 - P_{s_i}) \tag{11}$$

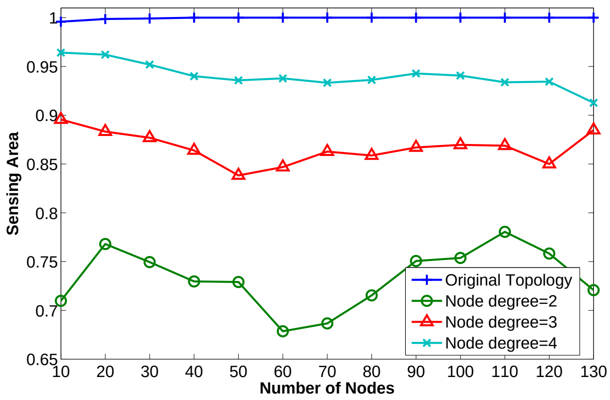

Fig. 5 Effect of change in number of nodes on the average sensing area.

where n is the number of sensor nodes covering a particular point and P_{s_i} is the sensing probability of a point for ith sensor. The more the active number of nodes, the higher is the total sum of P_{s_i} leading to an exponential increase in the overall sensing probability. The possibility of having more active number of nodes is only possible with network nodes having better harvesting opportunities available to them. In this manner, nodes can increase the sensing radius, which on the other hand increases the possibility of detecting an event.

In order to demonstrate the sensing area covered, the sensing radius was set equal to the transmission range and node degree was gradually decreased with each node working as an active node. Figure 5 shows the comparison between the sensing coverage area against the varying node density. With the increase in node degree, the sensing radius increases, and therefore increasing the network coverage and resulting in an increase in sensing coverage area. Similarly, as the node degree decreases, the sensing coverage area also decreases. Therefore, a network with high degree of connectivity provides better sensing coverage in the covered area.

In order to characterize the design challenges and the new performance parameters, it is important to analyze the availability of solar radiations and the similar size for the solar panels in different parts of the world. Therefore, in the next section, we provide a detailed overview of the solar radiation availability.

4 Solar Radiation Availability for Harvesting Energy

The renewable energy sources such as solar radiations are considered, which seems most adequate to power the sensor mote battery. Photovoltaic modules can be used to convert solar radiation into electricity. The output power of a photovoltaic module is directly proportional to the solar radiations captured and is expressed as:

$$P = \frac{G}{1000} A\eta(G, T_m) kW \tag{12}$$

Table 2 Data set specifications.

Name	Coordinates	Avg annual temp	Data (days)	Mean burst size	Max burst size
Valentia	51.93N,10.25E	11.4°C	5752	3.85	24
Bondville	40.06N,88.37W	11.0°C	4080	1.39	05
Sonnblick	47.05N,12.95W	-4.0°C	6936	2.35	18

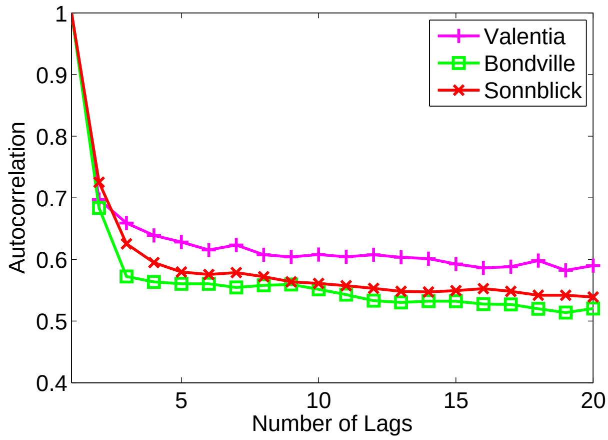

Fig. 6 Autocorrelation of daily solar irradiance unavailability.

Where G denotes to Solar radiations in W/m^2, A is the module area in m^2, and $\eta(G,T_m)$ is the module efficiency, which is dependent on radiations and temperature. A combination of Photovoltaic modules forms a Photovoltaic panel, which when combined forms a Photovoltaic system. A Photovoltaic system is characterized by its peak power ratings expressed in peak kW.

In order to analyze the battery requirements for a solar harvesting device in different regions of the world, solar radiation data-set was obtained from World Radiation Data Center (WRDC) for three different locations, Valentia (Ireland), Bondville (Illinois, USA) and Sonnblick (Austria) [5]. The solar data varies for different locations in terms of number of days. Therefore, the above locations were considered due to the data being available for longer duration i.e. 4080 for Bondville and 6936 for Sonnblick.

The location being considered vary greatly in solar radiation characteristics. For instance, due to harsh environment, Sonnblick has poor harvesting conditions whereas Bondville possesses better opportunity for harvesting, as evident from relatively higher average annual temperature of about 11°C from Table 2. However, we are interested in finding the expected number of consecutive days when harvested solar energy is less than a certain threshold. It is due to the reason that topology maintenance may be required for nodes with less or no harvesting opportunity. Therefore, the available data is further analyzed in the next subsection.

Table 3 Parameters settings in PVWatts.

Name	Coordinates	Peak Power	Array fixed Tilt	Azimuth	AC/DC derate factor
Valentia	51.93N,10.25E	1 KW	51.9°	180°	0.77
Bondville	39.83N,89.67W	1 KW	39.9°	180°	0.77
Sonnblick	47.80N,13.00W	1 KW	47.8°	180°	0.77

The power required to be in an active state for a various type of sensor nodes is not more than $1W$ [3]. Therefore, burst size for each site was computed as the consecutive number of days in which the daily received global solar energy is less than $0.2KWh/m^2$. The maximum and the mean burst size for each location in shown in Table 2. The mean varies between 1 and 4 indicating a variation existing between different locations. Similarly, the maximum burst size also shows the same behavior and demonstrates that, the optimal energy store sizes are not same.

In order to analyze the solar radiation availability dependence between consecutive days, let i be a binary random process represented as $X[i] \in \{0,1\}$, where $0 \Rightarrow$ the time slot in which the daily received solar radiation is above the minimum threshold value. The auto-correlation can then be computed as:

$$\rho[k] = \frac{E\{X[0]X[k]\} - E\{X[0]\}E\{X[k]\}}{\sqrt{\mathrm{var}\{X[0]\}}\sqrt{\mathrm{var}\{X[k]\}}} \tag{13}$$

where $E\{.\}$ and $\mathrm{var}\{.\}$ represent the expected value and variance of the random process. From the available data set for an ensemble of days, the results up to 20 lags for each site are shown in Figure 6. The results demonstrate that the first few lags are strongly correlated with variation as the number of lags increases. Similarly, the changing storage capacity and the battery load was also analyzed for energy depletion probabilities revealing that near perpetual operation is possible with solar harvesting sensors.

To further validate our analysis on the solar radiation availability and its capability to continuously power the WSN batteries, the PVWatts simulator [4] was used, which is developed by National Renewable Energy Laboratory (NREL) of Golden, Colorado. The simulator receives the input in terms of Peak power in kW, geographic location, tilting angle and azimuth angle and outputs the solar radiation availability for different areas of the World. The parameter setting used in PVWatts is shown in Table 3. The locations Bondville and Sonnblick vary slightly in coordinates (Table 3) when compared with the previous data-set due to the unavailability of the data with same coordinates. However, the effect on the solar radiations availability does not shows a big difference while the notion is to demonstrate that continuous harvesting opportunities remain available. Similarly, AC/DC derate factor is used for direct AC supply and can be subtracted in case of DC supply.

In order to generate a given amount of peak power (P_p), the number of modules required can be calculated by $N = [P_p/P\_nom]$, where P_nom is the nominal power of the Photovoltaic module. The few best Photovoltaic cells available in the market have P_nom ratio equal to $8.3W$ for an area of around $0.04m^2$ [29]. For powering

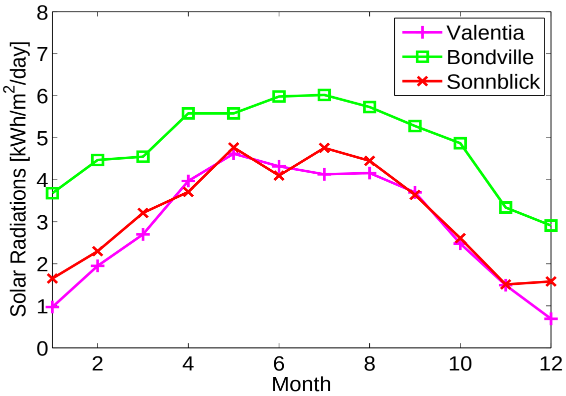

Fig. 7 Annual Solar Radiation Availability.

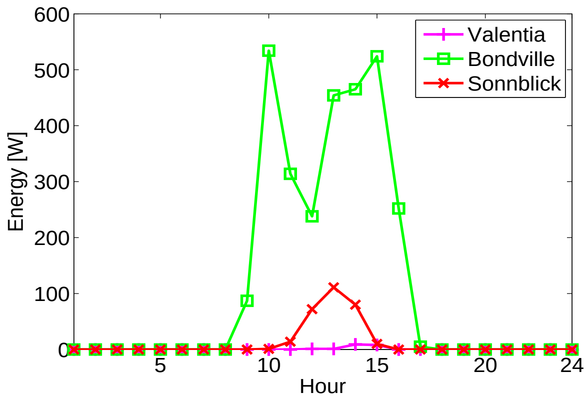

Fig. 8 Energy production of a 1 kW peak power photovoltaic cells in the three considered locations for the typical day of the month with minimum radiation.

the sensor battery, solar radiations availability measurements are important, which is shown in Figure 7 for the selected sites. It reveals the same behavior as witnessed earlier from the other data set, that solar radiation availability varies throughout the year. Similarly, the Photovoltaic module installed in Bondville has a much more constant energy availability with respect to both Sonnblick and Valentia; overall, the Bondville system generates 60% more energy with respect to the one in Valentia. It is worth mentioning that the lower the solar radiation production, the more is the size of Photovoltaic module for the continuous operation.

To estimate the PV system size that can be used to power a sensor mote in the different sites under consideration, the energy production of an average day (fifteenth day) of the worst month (December) is computed. The result is shown in Figure 8, versus the time of the day. It is very obvious that the production would remain to zero at night, and peaks around noon, when the solar radiation is maximum. Similarly, it reveals that for Bondville and Sonnblick, requirement of a sensor node can easily be

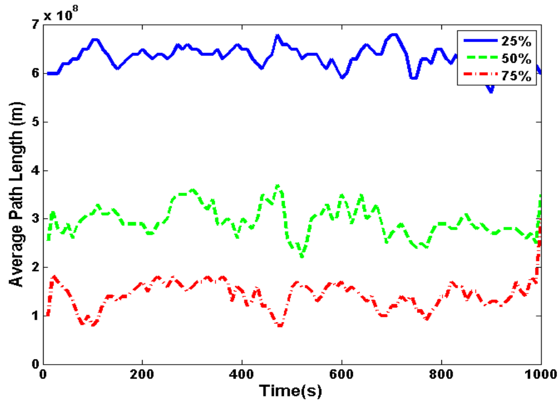

Fig. 9 Average Path Length per unit time for networks with nodes equipped with energy harvesting capability.

fulfilled. On the other hand, the values peak to around 9W in the noon for Valentia, which seems sufficient. Therefore, it reveals that near perpetual operation is possible, while the photo voltaic module size can also be increased in the worst case scenarios of different locations. It is worth mentioning that the average temperature of the selected locations were well below the average temperatures in most regions such as Asia and Middle East. Due to this reason, the regions with temperatures more than the selected locations may have better harvesting opportunities.

To learn from the solar radiations availability and from the performance evaluation of the last section, we now rephrase and summarize the deductions in terms of design guidelines that should be followed by a harvesting enabled topology control algorithms/protocols.

5 Harvesting Enabled Topology Control: Design Approach

For coupling the harvested energy with topology maintenance, we performed extra simulations by modifying the LEACH algorithm. The algorithm uses a round robin scheme where nodes that have been clusterheads cannot become clusterheads again for P rounds, where P is the desired percentage of clusterheads. Thereafter, each node has a $1/P$ probability of becoming a clusterhead in each round. At the end of each round, node that is not a clusterhead selects the closest clusterhead and joins that cluster. The clusterhead then creates a schedule for each node in a time based fashion to transmit the data. However, in simulations, we modified the desired percentage P in such a manner that $0.25, 0.5, 0.75\%$ of nodes are able to harvest $8W/day$ with a Photovoltaic cell of size $0.04m^2$ coupled with their batteries. In other words, we want to analyze the implications on Fault tolerance and Sensing coverage, when a proportion of nodes in the network have harvesting opportunity available to them. For experiments, the network of 100 nodes was deployed in an area of $100 \times 100m^2$ with transmission radius of $30m$. The energy distribution, node location distribution,

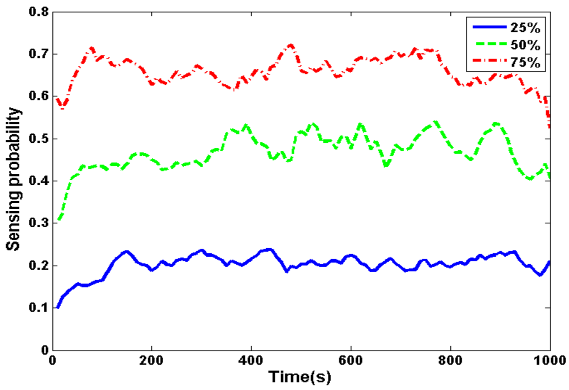

Fig. 10 Comparison between the sensing probabilities of the networks with nodes equipped with energy harvesting capability.

channel characteristics and energy consumption parameters of [17] were used in the simulations. All the results were averaged over 100 simulations runs.

Figure 9 shows the impact of nodes with harvested energy on the average path length of the network. Due to the change in the process of clusterhead selection, the slight variation is seen in every case as average path length is computed for each iteration. However, the results clearly demonstrate that the network with the highest number of energy harvesting nodes provides lower values of average path length which on the other hand provides better network reliability.

Figure 10 shows the sensing probability over the period of time with nodes having different harvesting opportunities available to them. In this experiment, fifty points in the network were randomly selected to analyze the possible number of nodes which can access those points while keeping in consideration the transmission radius of every node. The more the number points covered by the nodes, the higher is the sensing probability and vice versa. The results demonstrate that the increase in percentage of energy harvesting nodes enables to increases the sensing probability.

In order to analyze the feasibility of using solar energy provisioning for the wireless sensor network, LEACH algorithm was considered which uses a TDMA (Time Division Multiple Access) scheme for data transmission inside the network. It is assumed that every node transmits at its assigned time slot with a probability $\beta = 1$. Hence, in a network of n nodes, each node will transmit for $1/n$ of the total time and receive for $(n-1)/n$ of the total time. For such a network, the energy consumption for a node per day can be represented by:

$$E_{con} = t((\frac{n-1}{n})E_R + \frac{1}{n}(E_{Tx} + (E_{To} \times d^2))) \tag{14}$$

Where E_R is the energy consumed by the receiver circuitry, E_{To} is the energy consumed by the transmitter amplifier and E_{Tx} denotes the energy of the transmission circuit. Similarly, t represents the time in hours and d represents the distance.

For estimating the energy consumption of a node in a WSN, the classical energy consumption model proposed in [18] is used, which modifies the above equation to:

$$E_{con} = 24((\frac{n-1}{n})50 \times 10^{-9} + \frac{1}{n}(50 \times 10^{-9} + (100 \times 10^{-12} \times d^2))) \tag{15}$$

$$E_{con} = 1.2 \times 10^{-6} + (\frac{2.4 \times 10^{-9}}{n})d^2 \tag{16}$$

From above equation, it can be deduced that for a large sized network where nodes are placed closed to each other; the energy consumption of every node becomes very low, thus providing a longer lifetime. Now for these nodes, the energy harvesting capability can be approximated as:

$$E_{cell} = \eta E_{in} A_c t \tag{17}$$

Where E_{in} is the maximum power point of the solar cell with η being the efficiency and A_c is the area of the solar cell. If we calculate the solar energy approximation for an area of $0.04m^2$ in the area of Sonnblick where in a span of 24 hours, the maximum power point is $1W$ for 2 hours and an average of $8W$ for another two hours, then the total energy generated by the solar cell will be:

$$E_{cell} = (0.72)\eta \tag{18}$$

It is worth noting that for Sonnblick, the peak around noon goes maximum to $100W$. By comparing above equations, it can be observed that for a large sized network where nodes in the network are placed close to each other, even with a low efficiency solar cell, longer network lifetime can be achieved. In such a case, the lifetime of the energy harvested sensor node will be bounded by the charge discharge life of the battery and other variants.

Energy is one of the scarcest resources in wireless sensor networks. When used in applications such as data gathering for environmental monitoring, for sensor nodes, using a power supply from a fixed utility and/or manual battery recharging may not be technically and economically viable. Therefore, in order to save energy, researchers focused on reducing the topology, in which nodes are allowed to go into sleep mode while ensuring connectivity. In addition, the reduced topology is maintained with efforts of using as few numbers of messages as possible. Therefore, the focus in the design of topology control remained on reducing the communication links and the number of exchanged messages. Similarly, efforts were also made to achieve coding efficiency when visual sensors are considered. In this context, the design requirements were the spent energy, algorithm convergence time, connectivity, and choosing a best energy value to reset a topology for maintenance purpose.

In the presence of energy harvesting devices, the previous design requirements in the context of topology control are not important. Therefore, the focus needs to remain on the issues which were compromised for achieving the energy efficiency such as fault tolerance. Similarly, sensing coverage region was also compromised for nodes sleep/wakeup operation to achieve energy efficiency. In this new scenario, topology control becomes a single phase maintenance process, which can monitor the harvesting opportunity continuously i.e. the nodes which are unable to harvest energy should be maintained by putting into a sleep mode. Some of the salient requirements/guidelines to be considered in the re-design of harvesting enabled topology control are as under:

– The construction of a reduced topology should not base on energy saving but on the basis of fault tolerance and sensing coverage region. For this purpose, robust topological structures can be ensured by setting a minimum transmission range of every node i.e. adaptation of the communication pattern based on the available harvesting opportunities.
– The solar radiation availability depends on different regions and locations. Therefore, duty cycling is required for nodes present in locations where energy harvesting is not possible or in cases of sudden node failure. In addition, the photo voltaic module size should also be considered for different nodes and locations i.e. nodes present in locations where the default node degree is high should be equipped with large modules.
– The size of the battery should be considered for sink nodes, which perform more processing tasks when compared with other nodes. In this context, the size of the photo voltaic module again becomes important with battery size modeling also playing an important role i.e. relation between battery consumption versus energy supplied by the solar panel.
– As the energy transference technology is gaining popularity, therefore, the nodes with better harvesting opportunities can be used as energy banks. As part of topology maintenance, the stored energy can be transferred later to other nodes with less harvesting opportunities for continuous operation.

6 Conclusions

The paper analyzes the solar radiations availability in different parts of the World based on the actual radiation data set. Based on the observations from the data, a redesign in the topology control process for harvesting enabled sensor network is analyzed for new performance parameters. It was analyzed that the solar radiations for harvesting energy can provide near perpetual operation. However, the photo-voltaic module size and location also needs consideration before the network deployment. In this context, the guidelines to be considered in the re-design were also summarized. On the other hand, empirical and mathematical findings reveal that harvesting enabled topology control can provide better fault tolerance and sensing coverage for a given network scenario with harvesting opportunities available.

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Hassaan Khaliq Qureshi received his Ph.D. degree in Electrical Engineering from City University, London, England in 2011. Earlier, he received the M.Sc., degree in Electrical Engineering with a first class honors from Blekinge Institute of Technology, Sweden in 2006. He is currently working as an Assistant Professor in School of Electrical Engineering and Computer Science (SEECS), National University of Sciences and Technology (NUST). Before moving to Sweden, he worked in A.E.S.L (Caterpillar) Private Ltd. as a service engineer and then after completing masters, served as a lecturer in Bahahuddin Zakariya University, Pakistan. He then moved to Germany and remained Research Assistant in Technical University of Dresden and worked on European Union OPERA project. He is also a recipient of EU Erasmus Mundus post-doctoral fellowship under STRONG TIES program. He serves as a reviewer for IEEE conferences, including Globecom, DCOSS. He also serves as a reviewer for Springer's Wireless Personal communications, Wireless Networks Journal, IEEE Transactions on Parallel and Distributed Systems and China Communications Journal. His main research interests include wireless channel modeling, Network optimization techniques, topology control, network reliability, and energy provisioning issues for infrastructure-less networks and graph theory.

Adnan Iqbal received his Ph.D. degree in Information Technology from National University of Sciences and Technology (NUST) in 2011. He is currently working as an Assistant Professor in Namal College – an affiliate college of Bradford University, UK. He has also worked at Stanford Linear Accelerator Centre (SLAC), California. His research interests include wireless channel modeling, reliable data delivery and software defined networking.

Waqar Asif received his M.S., degree from School of Electrical Engineering and Computer Science at the National University of Sciences and Technology, Pakistan. He is a Ph.D. student at City University London, UK. His current area of research is the impact of change in average path length on reliable infrastructure-less networks and biological networks.