

Topology Preserving Map for Wireless Sensor Networks Equipped with Directional Antennas

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Abstract— The use of directional antennas in mobile wireless networks has emerged recently due to their numerous advantages such as high gain, low interference and low transmission power to reach the same distance as omni antennas. However, directional antennas limit the coverage and connectivity in the network. In this paper, we propose an algorithm to calculate a topology preserving map for wireless sensor networks using directional antennas. In the literature, topology mapping have been proposed for sensor networks equipped with omni antennas; however, to the best of our knowledge none of the existing work has considered the use of directional antennas in sensor network topology mapping. The application of existing algorithms in directional sensor networks will consume significantly high energy, as it requires transmitting the number of sectors times more beacon messages to cover the omni antenna range. Thus in this paper, a novel beacon forwarding algorithm limiting the number of forwarding sectors based on packet received direction is proposed. The simulation results show that it is possible to generate an accurate topology preserving map can be generated by only forwarding beacons in total of 135° angle. Moreover, the energy and the number of edges used to generate the topology map can be reduced by nearly 50% compared to the topology map generation with omni antennas based on received signal strength and hop count.

Keywords—Directional Antennas, Localization, Topology Map, Wireless Sensor Networks

I. INTRODUCTION

With the recent advancements in Internet of Things, Wireless Sensor Networks (WSNs) have found their way into wide variety of real-world applications such as environmental monitoring, medical, security, smart building and so on [1]. As a result, it is increasingly getting a challenging for WSNs to communicate efficiently due to interference and spectrum issues [2, 3]. Therefore, equipping sensors with directional antennas and using new frequency bands for communication have gained significant attention in the recent past to improve the communication of WSNs [4].

The use of directional antennas in WSNs reduces the interference, network traffic and energy consumption due to the reduction in unwanted packet transmission in the network [4]. However, it also introduces new challenges and limits the use of existing sensor network protocols. Certain issues have already been addressed in the literature such as the requirement of directional MAC protocol for WSN [4]–[6], directional antenna

design for WSN [7], and connectivity issues in WSNs with directional antennas [8].

Location awareness of sensor nodes is a prevailing issue for WSNs that has been addressed in many different aspects in the past. One of the popular ways is to find the physical coordinates of sensor nodes using range based or range free localization algorithms. In range based algorithms, range parameters such as Received Signal Strength (RSS) [9], Time of Arrival (ToA) [10] or Angle of Arrival (AoA) [11], are used to calculate the coordinate of sensor nodes. However, these range parameters are sensitive to the communication effects, such as noise, interference and multi-path, thus the accuracy of those algorithms are highly dependent on the environmental characteristics [12]. In range free algorithms, coordinate calculations do not depend on any range based parameters; however, these algorithms typically require a large number of anchor nodes or specific anchor node deployment scheme to calculate the coordinates accurately [13, 14]. Due to these drawbacks in physical localization, topology mapping algorithms have been proposed [15, 16], which finds out the coordinates of sensor nodes in a different coordinate system whilst preserving the node connectivity information. However, a little has been done for WSNs with directional antennas, despite some work based on range-free [17] and range-based [18, 19] techniques. To the best of our knowledge, none of the existing work has addressed the use of directional antennas in WSN topology mapping.

Therefore, this paper proposes a Topology Preserving Map (TPM) algorithm for WSNs using directional antennas. We have proposed a novel beacon forwarding method limiting the beacon propagation to a minimal set of antenna beams. When sensor receives a beacon, it calculate a weighting factor for all its beams, which is based on the direction of beacon reception and then the received beacon is forwarded using defined number of beams that have the highest weighting values. After the beacon forwarding process, each sensor is identified by a vector that contains the distance in hops to a set of reference/anchor nodes. This vector is called as Virtual Coordinate (VC) vector. Then the topology maps are calculated by taking the Singular Value Decomposition (SVD) of obtained Virtual Coordinate System (VCS). In the proposed algorithm, our objective is to optimize

the energy usage in the network and to reduce the network traffic. The novelty of this proposed algorithm compared to the TPM calculation proposed in [15] stems from the use of directional antennas for TPM generation and the novel beacon forwarding method that reduces unwanted beacon transmissions while significantly reducing the energy consumption, network traffic and interference.

The performance of the proposed algorithm is evaluated and compared using 2D and 3D sensor networks with three evaluation metrics; the accuracy of the generated TPM using topology preserving error, the total energy usage for transceiver, and transmission link usage. The results show that the accuracy of generated TPM maps using omni antennas and directional antennas is nearly same, however, total energy consumption is reduced by half compared to energy consumption in omni antenna TPM generation in both 2D and 3D networks. Moreover, the transmission link usage in both 2D and 3D networks are also reduced by 50% compared to link usage in omni antenna TPM generation.

The outline of this paper is as follows. Section II reviews the background of our work. Section III discusses the details of our proposed algorithm and Section IV presents the results. Finally, Section V presents the conclusions and future work.

II. BACKGROUND

This section discusses the previous work done in physical localization using omni and directional antennas, and topology mapping schemes for WSNs with omni antennas.

A. Physical localization with omni antennas

Physical localization techniques estimate the actual positions of nodes in the network and those techniques can be grouped into two categories, namely, **range based** and **range free**.

In range based algorithms hardware devices are used to measure the range based parameters such as RSSI, ToA and/or AoA. In RSSI based localization algorithms, theoretical [20, 21] or empirical models [9, 12] are used to estimate the distance from the signal strength of receiving packets. An empirical 3D localization method based on RSSI has proposed in [22]. First, it localizes the anchor nodes using the RSSI of the signals received by other anchors and calculates a modification factor based on the location error. Then the unknown node locations are calculated by Multi-Dimensional Scaling (MDS) technique incorporating the calculated modification factor. The localization methods based on time difference of arrival (TDoA) estimates the coordinates of an unknown node by anchor nodes' coordinates based on the time difference of arrival from those anchors to the node. To be able to calculate the coordinates, it needs at least four anchors [23]. Furthermore, ToA based localization, requires the sensor timers to be synchronized, which is often challenging task in practice. To overcome this requirement, researchers have proposed the use of Round-Trip ToA (RToA) [24] and Two Way ToA (TW-ToA) [25]. In addition, ToA localization does not address issues associated with obstacles and radio frequency signal propagation effects such

as high sensitivity of range based measurements to multipath propagation, fading and attenuation in the environment.

In range free localization algorithms, the locations of nodes are obtained without using any special hardware simply relying on the connectivity information of nodes [13, 14]. A range free 3D localization algorithm named NTLDV-HOP has proposed in [26]. First, it localizes anchors and finds a hop distance error correction value for each anchor. In second part, the algorithm calculates the locations of unknown nodes incorporating the error correction values with the hop matrix. However, the accuracy of these algorithms heavily depends on the number of anchor nodes and their deployment and hop distance estimation.

B. Physical localization with directional antennas

Jiang et al. proposed a localization scheme for a WSN with rotatable directional antennas [18]. By observing the variation of the RSSI values of the periodic beacons of anchors, sensor nodes estimate the orientation relative to the anchor node. Then using the estimated orientations and known positions of two distinct anchor nodes, sensor coordinates were calculated. A localization scheme based on AoA and RSSI values from beacons received from two perpendicular directional antennas was proposed in [19]. The enhancements of using directional antennas in RSS fingerprinting-based indoor localization was discussed in [27].

A range free localization scheme for WSNs using mobile anchor nodes equipped with four fixed directional antennas is proposed in [17]. Moreover, range free WSN localization algorithms based on directional antennas are proposed in [28, 29]. In these methods, sensor locations are calculated based on the intersection of the areas covered by the beacons transmitted by multiple anchors. The coordinate of the centroid of the intersection area is assigned as the sensor coordinate.

C. Topology mapping algorithms

Topological mapping techniques are fundamentally different to physical localization techniques because in topology mapping only the arrangement of the nodes are considered, instead of the actual location of the nodes. In other words, the mapping schemes expect the relative distances to be accurate, not the physical distances. Thus, given the absolute position of a subset of nodes, global localization can be realizable [30]. However, to achieve this, the topological map should be isomorphic to the physical layout of the sensor network [15].

Several unsupervised learning algorithms have been proposed in [31], which uses eigenvalue decomposition for obtaining a lower dimensional embedding of the data. It provides a unified framework for extending Multi-Dimensional Scaling (MDS) [32], Isomap [33], Local Linear Embedding (LLE), and Laplacian Eigenmaps (LE) [31]. MDS [32] is a commonly used statistical technique in information visualization for exploring similarities or dissimilarities in higher-dimensional data from the complete distance matrix (similarity matrix), which is defined as the matrix of all the pairwise distances between points/nodes. Isomaps [33] is an extension of MDS to geodesic distance-based topology map generation. Again, the geodesic

distances are actual distances between nodes, which require expensive error prone distance estimators such as RSSI or ToA. Moreover, LLE and LE both use an iterative approach to preserve the neighborhood distances, the realization of which is infeasible in energy-limited WSNs [15].

Dhanapala et al. [15] present a method to obtain topology preserving maps of WSNs using virtual coordinates (VCs) of sensor nodes. In VCs, the layout information such as physical voids, shapes etc. are absent. To overcome that, singular value decomposition (SVD) of VCs was proposed in [15]. Furthermore, [15] show that transformation for topological map from virtual coordinates can be generated using a subset of nodes. However, when the number of nodes increases, the time required to generate the virtual coordinate matrix also increases. To overcome these issues, Maximum Likelihood - Topology Map (ML-TM) algorithm has proposed in [16], which relies on a distance based packet reception probability function. A binary matrix is used to represent the packet reception of sensor nodes at different locations of the mobile robot's trajectory. Then the maximum likelihood topology coordinates of sensors are extracted using the probability function for packet reception. Xu et al. [34] propose an algorithm for locating new coming nodes to the network based on polynomial mapping. In this algorithm, the pair-wise distance is obtained by geodesic distance measurement. Then a graph is constructed to represent the topological structure of the sensor networks and calculate the weight matrix and the sparse preserving matrix. Finally, physical locations of all unknown nodes are calculated by coordinate transformation.

However, these topology mapping algorithms cannot be used in WSNs with directional antennas as omni antennas transmit messages to all directions and have high connectivity in the network. To achieve such connectivity with directional antennas, sensor nodes need to transmit messages from all its directions and it will consume more when the number of directional antennas increases. And also, the advantages associated with the directional antenna networks, such as reduction in interference and traffic, cannot be achieved by using omni antenna algorithms directly in directional antenna networks. Thus, this paper proposes an algorithm to calculate TPM for WSNs with directional antennas while achieving the directional antenna advantages.

III. PROPOSED ALGORITHM

In this section, we propose the topology mapping algorithm for WSNs with directional antennas. We first briefly describe the network architecture and properties of directional antennas. Then we introduce the beacon transmission algorithm and finally the Topology Preserving Map (TPM) generation is presented.

A. Network architecture and assumptions

This paper concerns a WSN of which each node is equipped with $N_b > 1$ directional antennas having horizontal beamwidth $\alpha \in (0, 2\pi)$ and vertical beamwidth $\beta \in (0, \pi)$ (in 2D network

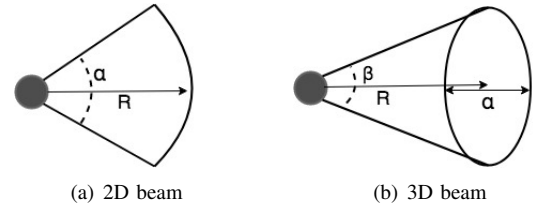


Fig. 1: Directional antenna approximated beam pattern

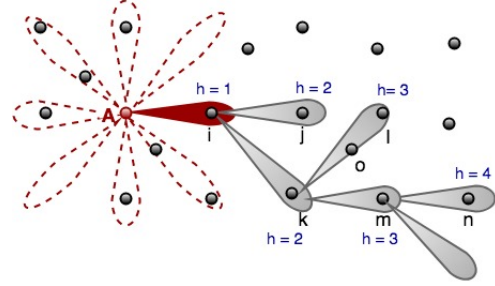


Fig. 2: Illustration of beacon transmission in 2D network

$\beta = 0$). The sum of the horizontal beamwidths α of the N_b antennas of each node is 2π . We assume that nodes have different beam orientations. For convenience, the beam ids are numbers starting from 1 to N_b and given in counter clockwise direction starting from the beam closer to the positive x-axis. The WSN contains sensor nodes and anchor nodes. Anchor nodes are randomly deployed in the sensing field and these nodes act as a reference point to generate the Virtual Coordinate (VC) vector. There are N number of sensors $S = \{s_i \mid i = 1, 2, \dots, N\}$ and M number of anchors $A = \{a_j \mid j = 1, 2, \dots, M\}$, where $0 < M \ll N$. Each node has a R communication range.

The position of a node is represented as a point (x, y) in 2D networks and (x, y, z) in 3D networks. Figure 1(a) and Figure 1(b) illustrates the approximated directional antenna beam pattern considered in 2D and 3D networks in this paper. We assume that side lobes can be suppressed by a suppression method [35]–[37] and similar to other localization schemes using directional antennas [17]–[19], we also ignore the side lobes in directional antenna beam patterns.

B. Beacon transmission algorithm for directional antennas

In the proposed topology mapping algorithm, anchor nodes broadcast beacon messages from all its beams $(1, \dots, N_b)$ and sensor nodes forward the received beacon packets from n_{fb} number of beams. Each node records a M length VC vector, which describes the number of hops to each anchor in the network. When an anchor broadcasting a beacon packet, it includes the node id and set the number of hops (h) as zero. Sensor nodes receiving beacon messages update the number of hop fields by one, update the VC vector and forward beacon messages to neighbors through the nominated forwarding beams. A beacon message is discarded; i) if its time-to-live timer expired or ii) the sensor node has already received and forwarded a beacon message from that particular anchor node in which the hop count is less than the newly received beacon packets' hop count.

Figure 2 illustrates an example beacon transmission in a 2D network when $n_{fb} = 2$ and $R = 1.5$. Anchor node A broadcasts beacon packets from all its beams. Consider the beacon flow of the first beam, which is highlighted in red color. Node i receives a beacon packet from anchor A , updates h field as one, records in its VC vector and forwards the beacon via two beams in the opposite direction. Then the beacon message is received by node j and k . They also forward the beacon via two beams in the opposite direction after updating the hop count and the VC vectors. This will continue until beacon message is discarded by a sensor node due to above mentioned two reasons.

Since we do not propagate beacons over all beams, the selection of forwarding beams is vital to generate an accurate TPM, which also trades-off the energy consumption of the sensor network. We propose to forward beacons via the opposite beam and its adjacent beams according to a weighting factor w^s , which is calculated for each beam s as in equation 1. The first n_{fb} beams that have the highest weighting factors are selected as the packet forwarding beams. If two beams have the same weighting factor, either one can be selected.

$$w^k = |s - s_r| \mod N_b \quad (1)$$

where s_r is the id of beacon received beam.

C. TPM calculation

This section describes the TPM calculation with the obtained VC vectors. We consider the same topology coordinate calculation method proposed in [15]. P , the $N \times M$ matrix containing the VCs of all the nodes and SVD of P can be denoted as;

$$P = U \cdot S \cdot V^T \quad (2)$$

where, U is a $N \times N$ unitary matrix, S is a $N \times M$ unitary matrix and V is $M \times M$ matrix, which is an optimal basis of P^T , i.e., V spans R^M .

P_{SVD} is an $N \times M$ matrix that describes each node with a new set of M -length coordinate vectors. It can be calculated as;

$$P_{SVD} = P \cdot V \quad (3)$$

Then, the topology coordinates $[x, y, z]$ of a node is given by the second, third and fourth columns of P_{SVD}

$$[x, y, z] = [P_{SVD}^{(2)}, P_{SVD}^{(3)}, P_{SVD}^{(4)}] \quad (4)$$

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed algorithm in a sensor network directional antennas and compare the results of TPM calculation in [15] proposed for omni antennas. We first describe the evaluation metrics used followed by the simulation parameters. Then, we discuss the performance evaluation and comparison of the proposed method.

A. Evaluation parameters

For this performance evaluation, we use three parameters, namely, topology preserving error, energy usage and link usage.

1) *Topology preserving error (E_{TP})*: To evaluate the accuracy of the calculated topology map, we used the E_{TP} error calculation method proposed in [15]. However, in [15], E_{TP} calculation is proposed only for 2D networks. Thus, we extend E_{TP} for 3D networks as shown in equation (5).

$$\begin{aligned} \text{Error pairs} &= \sum_{\substack{\text{all } xy \\ \text{planes}}} \sum_{\substack{\text{all } x \\ \text{lines}}} \sum_{\substack{\text{all } i, j}} I_{i,j} + \sum_{\substack{\text{all } xy \\ \text{planes}}} \sum_{\substack{\text{all } y \\ \text{lines}}} \sum_{\substack{\text{all } i, j}} I_{i,j} \\ &+ \sum_{\substack{\text{all } xz \\ \text{planes}}} \sum_{\substack{\text{all } z \\ \text{lines}}} \sum_{\substack{\text{all } i, j}} I_{i,j} \\ \text{Total pairs} &= \sum_{\substack{\text{all } xy \\ \text{planes}}} \sum_{\substack{\text{all } x \\ \text{lines}}} P_2^{N_x} + \sum_{\substack{\text{all } xy \\ \text{planes}}} \sum_{\substack{\text{all } y \\ \text{lines}}} P_2^{N_y} \\ &+ \sum_{\substack{\text{all } xz \\ \text{planes}}} \sum_{\substack{\text{all } z \\ \text{lines}}} P_2^{N_z} \\ E_{TP} &= \frac{\text{Error pairs}}{\text{Total pairs}} \end{aligned} \quad (5)$$

where, N_x , N_y or N_z is the total possible number of node pairs in each line. $I_{i,j}$ is defined as

$$I_{i,j} = \begin{cases} 1 & \text{if } i \text{ and } j \text{ are out of order compared to} \\ & \text{original placement} \\ 0 & \text{if } i \text{ and } j \text{ are same order compared to} \\ & \text{original placement} \end{cases}$$

where, $i, j \in N_{vl}$ or $i, j \in N_{hl}$.

2) *Energy usage (e_t)*: Energy is always a scarce resource in WSNs, it is paramount to efficiently use energy. Thus, energy usage is considered as one of our evaluation metric. The packet transmission and reception energy (communication energy) is typically higher compared to computation and sensing energy in WSN. Therefore, the objective of this method is to optimize the communication energy and from hereafter we have considered only the communication energy.

The packet transmitting energy E_{tx} and receiving energy E_{rx} can be calculated as in equation (6) and equation (7) respectively, which is based on the model proposed in [38, 39].

$$E_{tx} = lE_{elec} + lE_{amp}R^2 \quad (6)$$

$$E_{rx} = lE_{elec} \quad (7)$$

where, E_{elec} (Joules/bit) is the energy consumed in the electronics part of the transceiver in order to transmit/receive a bit of information, E_{amp} (Joules/bit/m²) is the energy consumed in the power amplifier part of the transmitter per bit, l is number of bits in a packet and R is the communication range. Compared to the omni antenna, directional antenna needs a less gain to transmit a beacon packet to a given communication range. Therefore, the directional antenna gain can be calculated as $G_o * 4\pi/\alpha\beta$ for 3D networks and $G_o * 2\pi/\alpha$ for 2D networks, when G_o is the gain of omni antenna [40, 41]. Since, E_{amp} is the component proportional to the transmission power, which is then proportional to the antenna gain, E_{amp} for directional antennas can be calculated as $E_{amp}^o * 4\pi/\alpha\beta$ for 3D networks

TABLE I: SIMULATION PARAMETERS

Parameter	Value
Sensitivity ^a	-80dB
Transmitting power P_{tx}	-50dB
ε	2.7
σ	9.6
E_{elec}	5×10^8 J/bit
E_{amp}	10^{11} J/bit/m ²
l	1000 bit
R	4m

^areceiving energy needs to be greater than the sensitivity to receive a packet

and $E_{amp} * 2\pi/\alpha$ for 2D networks, where E_{amp}^o is the energy consumed by the amplifier in the omni antenna.

3) *Link usage*(L_t): This parameter evaluates the total number of links (i.e. anchors to sensors or sensor to sensors) used to calculate the TPM. Reducing the link usage will result in lower interference, higher network capacity, and can also be resulted in reduced energy consumption.

B. Simulation parameters

For the simulation, we used MATLAB simulation software and the simulation parameters are given in Table I. To emulate a real communication link between transmitter and receiver, the propagation model proposed in [42] is used, which is given in equation (8).

$$P_{rx,i} = P_{tx,j} - 10\varepsilon \log d_{ij} + v_i \quad (8)$$

where, the received signal strength at node s_i is $P_{rx,i}$, the transmitted signal strength of the signal at node s_j is $P_{tx,j}$, the path-loss exponent is ε , the distance between node s_i and node s_j is d_{ij} , and the logarithm of shadowing component with a σ standard deviation on node s_i is v_i .

C. Performance evaluation

The evaluation is carried out in two aspects. First we generate the TPM and plot it in a Cartesian coordinate system to verify that the method has being able to preserve the shape of the network accurately. Then, we evaluate the accuracy of the map against the number of forwarding beams.

1) *Topology maps*: In this evaluation, we consider two 2D WSN networks and two 3D WSN networks. First 2D network is a sparse network with 700 sensor nodes as shown in Figure 3(a). A circular shape network with three voids and 496 sensor nodes is considered as the second 2D network, and it is shown in Figure 3(c). A spherical shape network and a T-joint shape network with 512 and 400 nodes respectively are considered as the two 3D networks. Figure 3(e) and Figure 3(g) presents those two 3D networks respectively.

For the initial TPM calculation, we consider $N_b = 8$, $n_{fb} = 3$ and $M/N = 0.1$. Figure 3(b)-3(h) shows the generated TPM using directional antennas for the four networks. From the figures, it can be seen that the generated maps are nonlinearly scaled and rotated compared to the physical map. However,

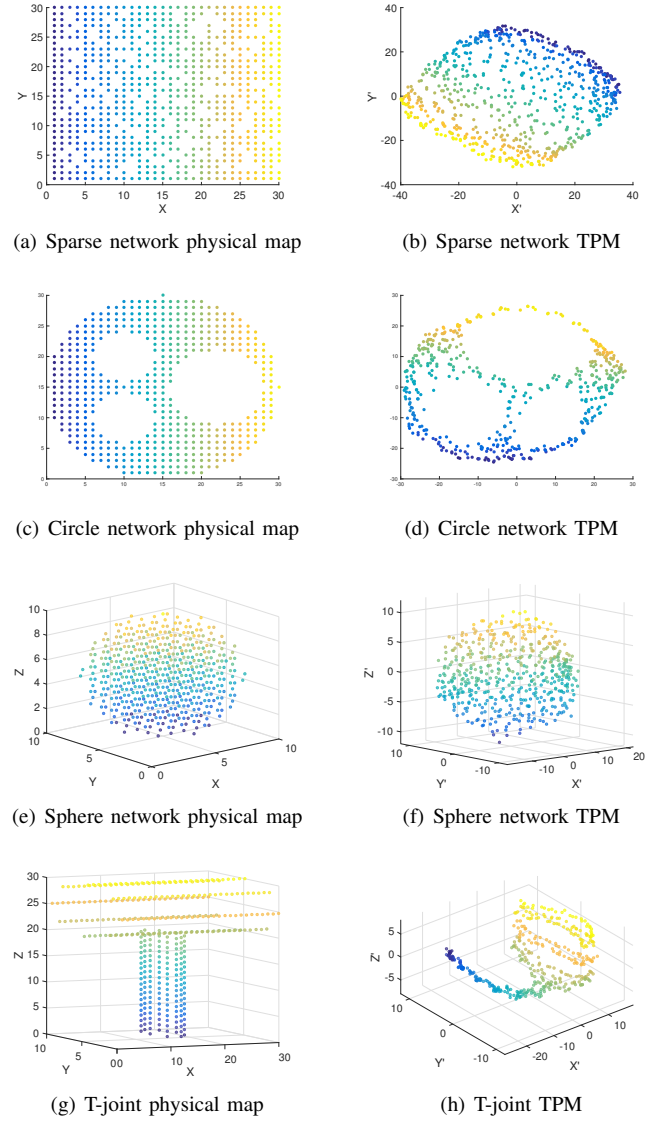


Fig. 3: Physical maps vs. TPMs

generated maps have been able to preserve the network shape with the voids. For an example, in Figure 3(d), the three voids in the physical map are clearly visible with the shape of the network. Moreover, in 3D T-joint shape TPM map in Figure 3(h), the shape of the network is well preserved.

2) *Accuracy vs number of forwarding beams*: This section discusses the accuracy of the calculated TPM against the number of forwarding beams (n_{fb}). We changed the total number of beams (N_b) in a nodes from 4 to 32 and results are presented in Figure 4. It is visible that the pattern of E_{TP} variation is same for all the four networks even though they have different E_{TP} values. Moreover, the highest accuracy can be achieved by forwarding beacon packets from half of the beams in a sensor node. But, in some cases it is less than the half. For an example, in Figure 4(d), the highest accuracy can be achieved by 12 forwarding beams, which is less than 16. Thus, we consider the coverage angle of all beams to find the minimum value for n_{fb} for a given network.

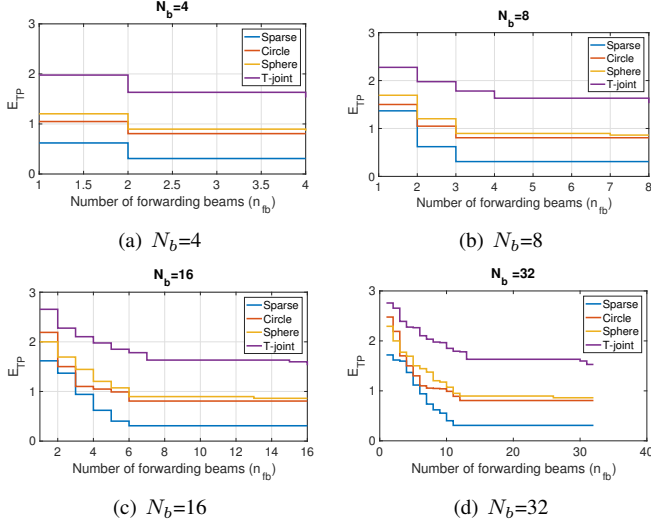


Fig. 4: Sparse network

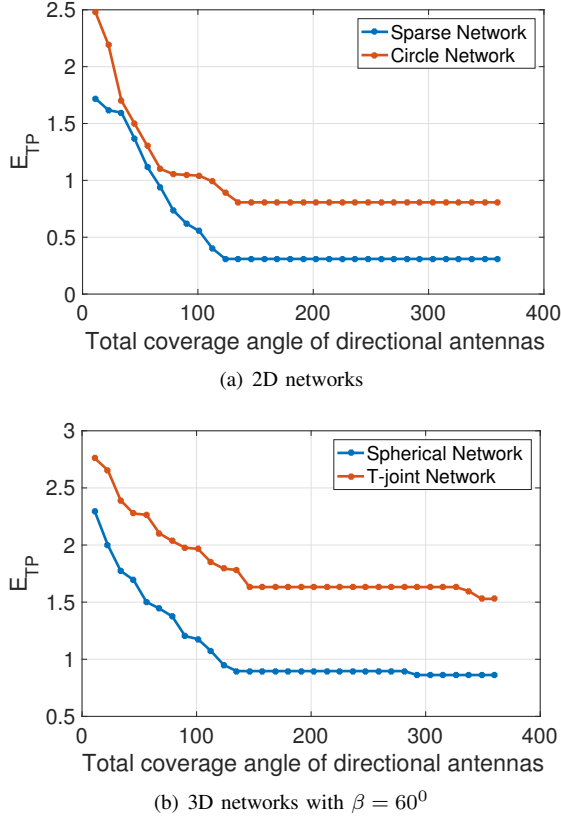


Fig. 5: Accuracy vs total coverage of directional antenna

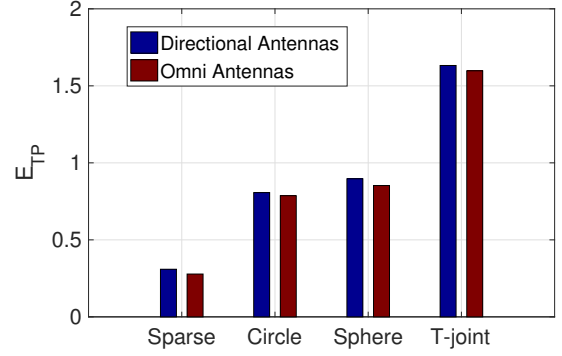


Fig. 6: TPM accuracy comparison with omni and directional antennas

The total coverage angle of all forwarding beams is calculated as αn_{fb} . We varies the total coverage angle from 0° to 360° and calculate the E_{TP} of generated maps. The calculated E_{TP} for the 2D networks are shown in Figure 5(a) and for the 3D networks are shown in Figure 5(b). In 3D networks β considers as 60° .

From Figure 5(a) and Figure 5(b), it can be seen that when coverage angle increased beyond 135° , the E_{TP} errors do not decrease. As a result, we can conclude that the lowest E_{TP} can be achieved by approximately covering 135° in the opposite direction of the beacon reception irrespective of the network shape. The reason for the forwarding packets in the opposite direction is to reduce the backward packet propagation. If the same packet is back propagated to a node, the packet will be discarded. As a result increasing the transmission angle beyond 135° does not increase the accuracy of the calculated TPM. On the other hand, by restricting the packet forwarding angle to 135° , the unwanted beacon transmissions in the network can be significantly reduced and this is one of the main advantages of using directional antennas in the network, which directly contributes to the low energy consumption. Moreover, from this result, we can find the optimal value for n_{fb} as, $n_{fb} \geq \frac{135 * N_b}{360}$.

D. Performance comparison

In this section, we compare the proposed method with TPM calculation using omni antennas, which is proposed in [15]. For the evaluation, the N_b was changed from 4 to 32, and n_{fb} was selected to have a coverage angle more than 135° degrees. This evaluation was done for all four networks discussed above and results were similar. Thus, we have presented the results only for $N_b = 8$ and $n_{fb} = 3$. The M/N ratio is considered as 0.1 for both algorithms. The comparison is carried out using the three evaluation parameters described in Section IV-A.

1) *Accuracy (E_{TP}):* Figure 6 shows the E_{TP} value for all four networks using omni antennas and directional antennas. It can be seen that error values of 2D and 3D networks are nearly equal in TPMs calculated using omni and directional antennas. Thus, we can conclude that using directional antennas, it is possible to achieve the same accuracy as omni antennas, even

TABLE II: ENERGY USAGE

	Total Transmitting Energy(J)		Total Receiving Energy(J)		Total Communication Energy (J)		Ratio of e_t^d/e_t^o
	Directional	Omni	Directional	Omni	Directional (e_t^d)	Omni (e_t^o)	
Sparse	0.0996	0.1988	0.3472	0.5286	0.4468	0.7274	0.6142
Circle	0.1404	0.2804	0.4338	0.6764	0.5742	0.9568	0.6001
Sphere	0.6156	1.4677	0.9264	1.7591	1.542	3.2268	0.4778
T-joint	0.3266	0.5335	0.4632	1.2244	0.7898	1.7579	0.4492

though directional antennas limit the connectivity in the network. Additionally, TPM calculation with directional antennas performs better in terms of energy consumption and link usage compared to the TPM calculation with omni antennas, which is discussed in the following sub sections.

2) *Energy usage (e_t)*: In this section, we compare the total energy usage for packet transmission and reception in the two networks with directional antennas and omni antennas. Table II illustrates the communication energy usage of four networks. Omni antennas broadcast packets in all 360° angle, whereas directional antennas consist of a lower coverage angle for the same distance. Since, omni antennas are broadcasting beacon packets in all directions, all the neighbors receive beacon packets even though they already have that information. In contrast, our approach limits the forwarding beams and therefore unwanted packet reception has been reduced. As a result total energy consumption on packet reception is lower in networks using directional antennas than omni antennas. In all four scenarios, TPM calculation with directional antennas consumes approximately half of the communication energy consumed by the TPM calculation with omni antennas.

3) *Link usage (L_t)*: This section compares the number of links/edges used in the network to generate the TPM using directional antennas and omni antennas. Table III presents the total number of link usage in all four networks. As directional antennas are forwarding packets to the neighbors in the selected forwarding beams, number of edges used in directional antennas is significantly less compared to omni antennas. From the column three of the Tables III, it can be seen that the directional antennas approximately uses only half of the links to generate the TPM compared to omni antenna TPM generation. Thus this reduces the network traffic, interference and also increases the energy efficiency of the network.

TABLE III: LINK USAGE

	Total links used to generate TPM using		Ratio of L_t^d/L_t^o
	Directional Antennas (L_t^d)	Omni Antennas (L_t^o)	
Sparse	3221	6760	0.48
Circle	2486	5277	0.47
Sphere	5900	13424	0.44
T-joint	2335	5426	0.43

V. CONCLUSION AND FUTURE DIRECTIONS

This paper proposed an algorithm to calculate a topology preserving map (TPM) for WSNs equipped with directional antennas. The use of directional antennas in WSNs has become popular in recent past due to advantages such as high gain, low interference and low energy usage. On the other hand, use of directional antennas limits the connectivity in WSNs compared to omni antennas. Thus, we proposed a novel beacon forwarding strategy using a minimal number of beams at each sensor to generate an accurate topology map while achieving the advantages associated with directional antennas. Each sensor forwards the beacon packets from a defined number of beams and those beams are selected based on a weighting factor calculated using packet received direction. The proposed topology mapping algorithm depends on a virtual coordinate vector that each sensor records with respect to the hop count to anchor/reference nodes in the network. As the proposed algorithm finds the coordinates of sensors in a different Cartesian coordinate system, the anchor nodes do not need to equip with a GPS. In this paper, we have proposed a topology map calculation algorithm for static WSNs. However, this method can be applied to a dynamically changing WSN by restarting the algorithm after a sensor location change.

The performance of the algorithm was evaluated and compared with TPM generation with omni antennas. The results show that by forwarding the packets in total of 135-degree angle in the opposite direction of packet reception, an accurate topology-preserving map can be generated. Additionally, the energy and the number of edges used to generate the topology map using directional antennas have been reduced by nearly 50% compared to the topology map generation with omni antennas. Thus we can conclude that the proposed topology mapping algorithm has been able to generate an accurate topology map as with omni antennas and also it has outperformed the omni antenna TPM generation with energy usage and interference level/traffic in the network.

Moreover, using directional antennas for WSNs performance enhancement is still under investigation. Energy efficient routing [43] and clustering algorithms [44], symmetric connectivity in the network [45, 46] and antenna orientation for the best connectivity [47], are some of the examples. Additionally, WSNs applications with directional antennas, such as target tracking [48], is also an emerging topic in this field. Thus, using an optimized antenna orientation for TPM calculation and proposing a data collection algorithm with the proposed TPM

are some of the future directions that are under investigation.

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