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THE MULTI-HOP CLUSTER TRANSMISSION OF INFORMATION METHOD FOR SOLVING THE LOW CONNECTIVITY PROBLEM IN WIRELESS SENSOR NETWORKS WITH NON-UNIFORM DENSITY

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Abstract. *This study describes multi-hop cluster transmission of information (MHCTI). This method is an efficient approach for network modelling of sensor data transmission. In this framework, clusters of neighbouring nodes are formed. Collectively, these clusters can significantly improve the transmission of information. The method is based on network clustering and the coherent addition of transmission fields from closely spaced wireless nodes. MHCTI can improve the data transmission distance range and be used to address the problem of low network connectivity in cases of non-uniform wireless node density, consequently increasing the lifetime of the sensor network. To analyse the effectiveness of the proposed method, the network lifetime and connectivity of the MHCTI method were compared with those of previous approaches. Moreover, a simple adaptive algorithm was investigated. In this algorithm, phase shifts in the radiator are randomly selected, and the zone covering the sending cluster is controlled, resulting in improved network connectivity.*
Keywords: Clustering, Collective information transmission, Connectivity, Lifetime, Routing, Non-uniform density

1. **Introduction.** Wireless sensor networks (WSNs), one of the most rapidly developing research and development fields, originated as a result of recent advancement in the fields of wireless communication, microelectronics, and embedded microprocessors [1,2]. Spatially distributed autonomous devices, known as “sensor nodes”, monitor the physical or environmental conditions at various locations. These sensor nodes comprise the intricate system of a WSN. A few of the uses of sensor networks include habitat monitoring [6], target tracking, security surveillance (e.g., alert to terrorist threats [7]), hazard and disaster monitoring and relief operations, applications in the health industry [8], and domestic applications (e.g., smart environments) [3].

In establishing a WSN, one or more sinks (or base stations) are needed, and tens or thousands of sensor nodes are dispersed throughout an area. Following the command of an application or process, the task of the sensor nodes is to gather information from the environment [3]. The sensor nodes assess variables such as temperature, light, vibration, noise, and radiation [4]. After gathering specific data, the sensor nodes transfer the information to the node sinks or base stations for further data processing. The nodes typically utilise multi-hop routing to facilitate the transfer of data in the sensor network. Numerous methods and strategies have been proposed for the optimization of the data-route process performed in WSNs [5]. Generally, a multi-hop network needs to transfer the gathered data, and thus, a route between a source and destination has to be identified. Hence, at least one route must be identified to forward the necessary information. Two nodes should be placed in close proximity to each other to establish effective communication; otherwise, these nodes cannot send/receive radio frequency signals, resulting in a segmented network. Several environmental conditions may result in a failure of communication, such as increased noise in the channel, inappropriate sensor network setup, or node failure.

Numerous problems exist in data transport. For example, if a sufficiently large number of wireless nodes are to be placed in a certain region, an airplane or helicopter can be used to scatter these nodes at their respective sites [3,9]. Thus, the nodes are randomly dispersed and can be highly heterogeneous. Even in cases of manual installation, the nodes can still have sensors of varying densities in different areas, resulting in non-uniform spatial density distributions. Each node has a limited radio range; hence, if the nodes in a certain area are of low density, the network will be partitioned into groups, which results in the absence of communication. On the other hand, even if the nodes are positioned at a high density, certain relief features (e.g., natural barriers, ponds, and buildings) can still generate network partitions in which certain groups of nodes are excluded from the main part of the network. Moreover, "the degradation of energy" can also result in the partitioning of the network into separate groups. Because the energy reserves in the sensor nodes are limited, energy depletion will eventually result in the failure of nodes.

As a sensor network performs its processes, data-transmission channels are simultaneously formed. A system of wireless nodes comprises these data-transmission channels, allowing the passage of information to corresponding reception points. The task of facilitating the transfer of data is unevenly distributed among the different nodes. For example, the nodes surrounding the point of collection and processing of information have maximum loads because all of the data channels pass through them. The effect of an increase in the uneven distribution of loads between nodes is evident when the wireless nodes are accidentally deployed. For instance, large groups of nodes can be connected by several sites. In this scenario, the connecting nodes experience more rapid energy depletion compared with the other sites. If these connecting sites fail, the network will be segmented. To avoid this unfavourable condition, the network should be implemented using a considerable over-positioning of cooperating nodes. A significant extension of sensor transmission range can ensure satisfactory overall connectivity among the nodes or toward the base station.

2. **Background.** For a sensor network to function effectively, favourable connectivity conditions should be established. Thus, techniques for improving connectivity have been the focus of several studies. As proposed, acceptable connectivity can be achieved by extending the sensor transmission range. One approach for achieving this goal is to employ cooperative transmission [11,12].

The aim of cooperative transmission is to achieve multi-hop cluster transmission of information (MHCTI). Remarkably, the realisation of coherent cooperative transmission is possible because of the ability of sensor nodes to function as virtual antennas for a source node. This cooperative transmission is highly beneficial to the transfer of identical information because it enables the accumulation of transmission power among different nodes. This process increases the sensor transmission range, which significantly improves network connectivity.

The "cooperative transmission" concept was proposed in two recent studies [11,12]. According to a previous study, the aforementioned concept can increase the transmission range and reduce energy consumption. For coherent cooperative transmission to be possible, all nodes transmitting the same signal should be transmitting the signal synchronously. Furthermore, the emitted waveforms should be superimposed on a physical medium. Hence, the detection at the receiver side can be significantly improved. A base station and N sensor nodes comprise a coherent transmission system (Figure 1). In a conventional "incoherent" transmission system, the sensor nodes transmit their signals during data transport without considering the amplitudes and phases of the signals. Therefore, the power of the signals that accumulates at the base station is merely proportional to the number of sensor nodes (N). Meanwhile, in coherent transmission, the sensor nodes transmit their signals in a manner that facilitates the coherent addition in "amplitude" of the signals combined at the base station. Thus, in coherent transmission, the combined signal power is proportional to the square of the number of sensor nodes (N^2). Coherent transmission increases the power by a factor of N. That is, compared with incoherent transmission, coherent transmission can significantly reduce energy consumption by decreasing the transmission power of each station by a factor of N while maintaining the same amount of power received at the base station. Furthermore, with the increase in transmission range, the connectivity of the entire network is improved. Finally, the presence of node isolation and division in the network, particularly for large and sparse networks, is eliminated [13].

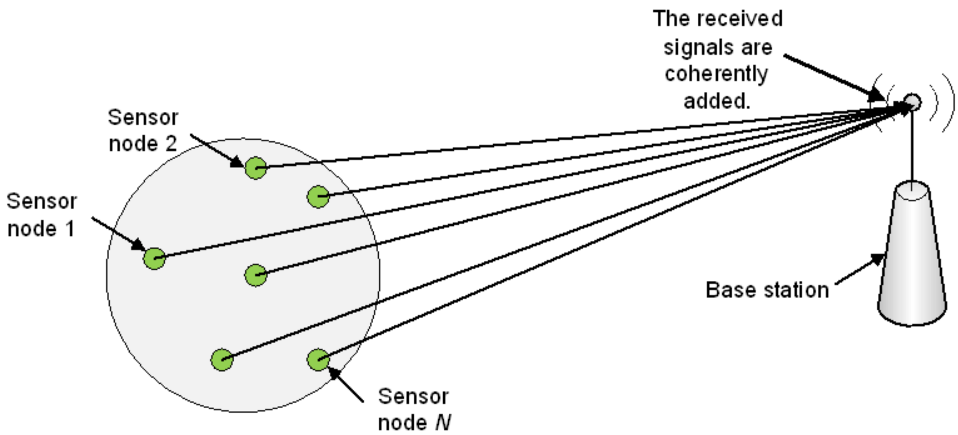

Figure 1. Concept of a coherent transmission system

3. **Related Work.** Previous studies [1,2,14] have provided a general overview of WSNs. The present study focuses on cooperative transmission in WSNs as a means of improving connectivity under non-uniform density conditions. This approach was previously demonstrated in the literature using three distinct approaches: multi-hop, data flooding, and cluster-based.

Multi-hop relaying is highly dependent on the physical channel. The multi-hop scenario, which is also regarded as a multi-dimensional relay channel, allows communication between nodes [15]. This approach has been proven to optimally distribute network resources in terms of information theoretic metrics [16]. However, this approach is inappropriate for increasing scenario sizes because the number of transmitted bits per square metre decreases quadratically with the size of the network [17,18].

Previous studies [19,20] proposed the opportunistic large array (OLA) as an alternative approach where the network is flooded with a message that needs to be transmitted. According to the OLA method, a received signal can be transmitted various times via neighbouring nodes, all of which function as relay nodes. Constructive interference is created while the nodes that transmit the desired signal flood the network. Similarly, a few studies [11,21] have demonstrated an approach in which the signal is overlaid with white noise, which is used to increase the probability of creating constructive interference. Using a wave-front technique, a message transmission is flooded through the network. The recipient nodes, following use of the accumulating cooperative transmission technique, will transmit a message several times, thus resulting in a considerable amount of overhead and energy usage for the entire network. However, the nodes are not synchronised, and the receiver does not provide feedback; therefore, the maximum constructive interference involved in these strategies can only be observed at some random point in the transmission range.

Further studies on this subject led to the development of the cluster-based approach [22]. This approach primarily aims to establish clusters of nodes that jointly transmit messages [1]. In addition, a related study [23] utilised an approach that achieves cooperation in sensor networks. In the former approach, clusters of several sensor nodes are built, and multi-hop transmission is then applied on a per-cluster basis. By simultaneously allowing transmission in all sensor nodes, virtual multi-input and multi-output channels are established. Furthermore, because the source can transmit the message using less power, a direct transmission toward the destination is unnecessary. However, management of the clusters is necessary in this type of scheme. Based on the modified low-energy adaptive clustering hierarchy protocol, previous work [24] analysed the cooperative multi-input and multi-output transmission technique. This approach evaluates system performance to reduce energy consumption while increasing the lifetime of sensor nodes with uniform density. However, under this topology, the network capacity is relatively low compared with those of the previously mentioned approaches [18,25].

This study proposes a method of MHCTI because the clustering approach is an efficient approach for reducing energy consumption in wireless sensor networks. The proposed method aims to address the problem of low connectivity in sensor networks with non-uniform node densities. The proposed method determines whether nodes can be combined to achieve synchronous data transmission from a certain node to another. The signals received from the transmission nodes are added coherently, resulting in a significant increase in the transmission range of information within the network.

The increase in the transmission range allows isolated groups of nodes to be either established or restored to service. Moreover, an improvement in sensor connectivity and an increase in the coverage area are obtained. Transmission capacity should be systematically added to ensure that all data in the wireless nodes are synchronised. Solution sync generators can help coordinate data transmission in wireless nodes. These generators can primarily be obtained using phase-locked systems by following the standard approach [26,27]. No real arrays are present, and thus, the antenna array of the cluster is considered "virtual" with a non-regular structure.

4. **Assumptions.** As shown in Figure 2, the sensory network proposed in this study has an established topology. Identical nodes are randomly dispersed with non-uniform density in one plane or over a flat area. Several features are present in each node, namely a sensor, transceiver, microcontroller, and energy source. The nodes are very similar, and their parameters are constant. The nodes obtain the data, which are eventually gathered in the sensor network. In the model sensory network used in this study, the sole point

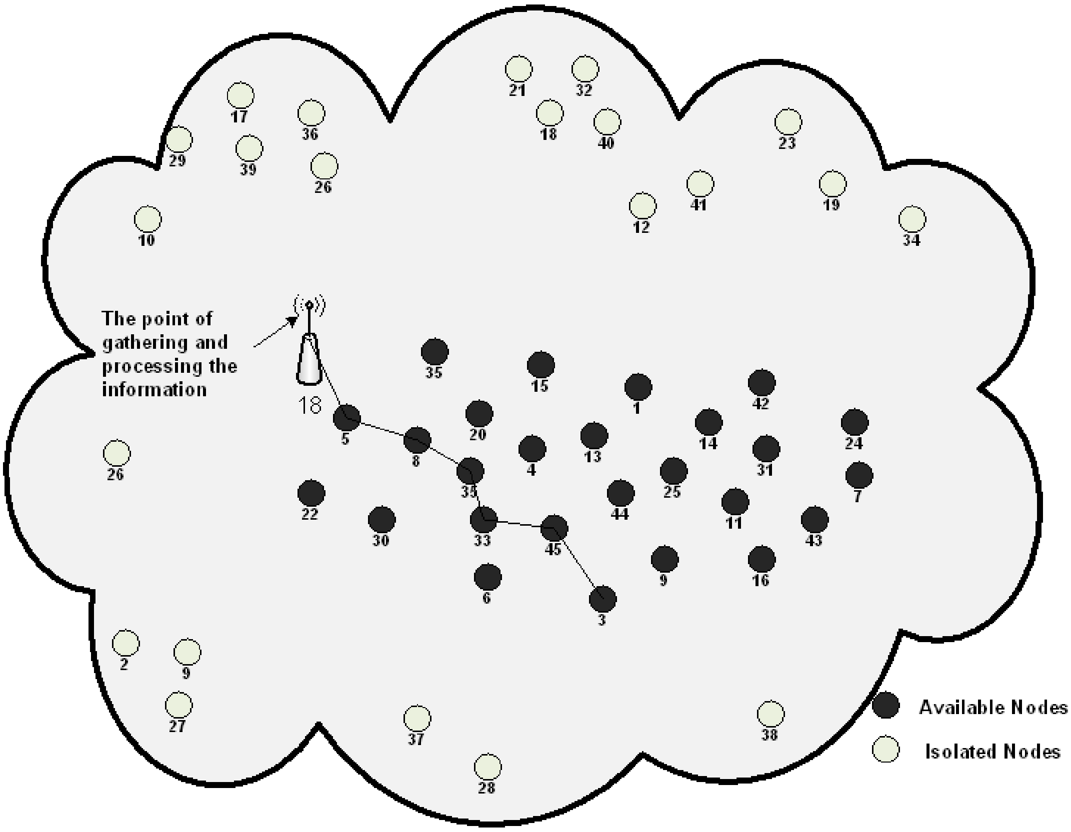

Figure 2. Model of non-uniform density sensor network

where the data are collected and processed is called the base station. The transmission range of every node remains constant because the determined power level of each node cannot be altered.

Channels can be located between a node and a base station. Likewise, channels can exist in a multi-hop network and along an omnidirectional antenna. Each node is assigned a fixed radius, R, which defines the organisation of the system of communication of the nodes (Figure 2). This arrangement (i.e., with a fixed R) ensures favourable communication between nodes; otherwise, the connection will fail (the radio communication range can be increased for MHCTI). To facilitate a systematic addition of power, the network is divided into cluster node groups. In addition, the radiation of transmitters synchronizes the frequency and stabilizes the phase.

5. **Contributions.** The contributions of this work can be summarized as follows:

- A sensor network model is proposed to address the problem of low connectivity in WSNs with non-uniform density.
- An improved energy-efficient cluster algorithm is presented to reduce network energy consumption.
- A coherent cooperative transmission of information method is used to significantly decrease energy consumption and increase transmission range.
- An alternative routing algorithm for multi-hop clusters is proposed.
- A simulation of the sensor network model with a non-uniform density is performed. The performance of the proposed model is compared with that of several related methods, and corresponding conclusions are drawn from this analysis.

6. **Multi-hop Cluster Transmission of Information (MHCTI) Method.** This method is based on the coherent addition of fields from closely spaced wireless nodes using the principle of coherent cooperative transmission of information [13]. Neighbouring nodes are combined into clusters. If a node needs to transmit information to the base station, the information is relayed to other nodes in the cluster. The nodes in the cluster synchronously transmit the data to the next hop node. At the reception point, the summed signal and electric field intensity may increase as a result of interference. Figure 3 shows three nodes with their emission ranges. Nodes 1, 2, and 3 are in the same cluster. Thus, if node 1 needs to transmit information to the base station (sink node 4), which is quite far, it sends the information to other nodes in the cluster (nodes 2 and 3). The nodes in the cluster transmit the data synchronously to the next hop node (sink node 4). The summation signal of the cooperative transmission results in an electric field intensity sufficient to reach sink node 4.

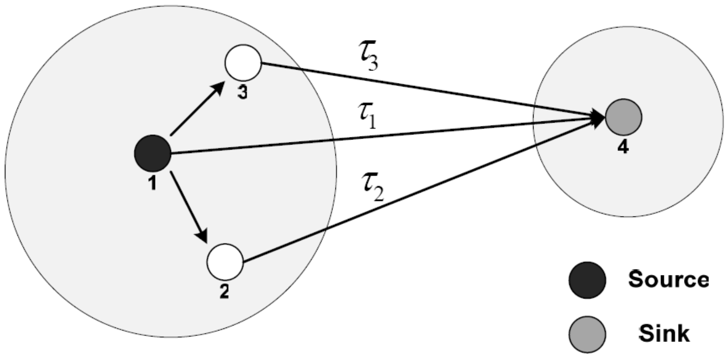

FIGURE 3. Electromagnetic waves from three transmitting nodes that combine coherently at the receiving node

Figure 3 illustrates the power addition of the three transmitting nodes. If the transmitted electromagnetic waves of the three nodes are of the same amplitude and perfectly coherent, the amplitude of the received wave is three times that of each component wave. Consequently, the channel capacity is increased. For a channel with adaptive white Gaussian noise, the channel capacity is

$$C = W \log_2 \left(1 + \frac{P_r}{\sigma^2}\right) \tag{1}$$

where W is the bandwidth in Hertz, σ^2 is the adaptive white Gaussian noise dispersion, and P_r is the average power received. When each node transmits its own information independently, P_r is equal to the summation of each transmission power multiplied by their respective attenuation. For identical attenuation a, identical transmission power P_t, and N transmitting nodes, P_r is equal to aNP_t. However, if the signals combine coherently, the average power received can be written as [13]

$$P_r = aN^2 P_t, \tag{2}$$

where P_r increases with the square of the number of transmitting nodes. At the receiving node, the expression is written as

$$r(t) = \sum_n \alpha_n e^{-j2\pi \cdot f\tau_n} s(t - \tau_n), \tag{3}$$

where $s(t)$ is the baseband signal in the transmitter, α_n is the amplitude, and τ_n is the delay time.

7. **Proposed Sensor Network Model.** The proposed sensor network model for MHCTI is shown in Figure 4.

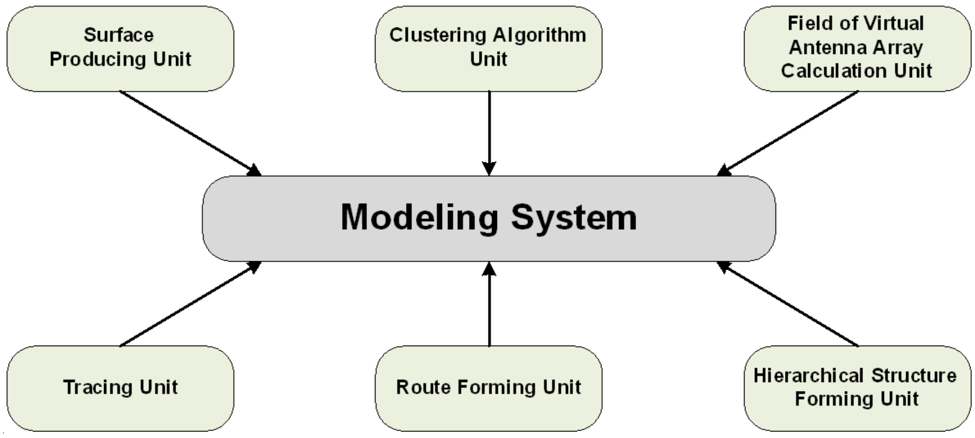

FIGURE 4. Proposed sensor network model

Four main units are presented:

1. Surface-producing unit
2. Clustering algorithm unit
3. Field of virtual antenna array calculation unit
4. Routing algorithm unit

7.1. **Surface producing unit.**

7.1.1. *Radio propagation model.* The antenna in each node is an electric dipole antenna, which is omni-directional in the plane $z = 0$. All dipoles are distributed on a plane ground surface and vertically oriented (Figure 5).

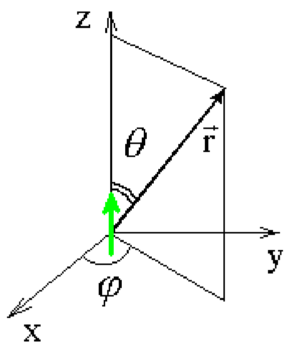

FIGURE 5. Radiating dipole orientation

The complex amplitude of the electric field intensity produced by an electric dipole radiator on the ground ($z = 0$) at a distance r from each node is calculated using the empirical formula obtained for the surface channels [28]:

$$E = E_s \left(\frac{r}{R}\right)^{-d} \exp\left(i(\omega t - kr + \varphi)\right), \tag{4}$$

where the sensitivity field E_s is the minimum field that a neighbouring node can detect, d is the degree of attenuation of the field and varies from $d = 1$ (for a model of free space) to $d = 2$ (for a model of radio wave propagation over a conducting surface), ω is the angular frequency, t is time, k is the wave vector in free space, and φ is the phase. Given that all nodes in the cluster are synchronised, the common multiplier exp (ωt) is omitted, and the electric field can be described as:

$$E = E_s \left(\frac{r}{R}\right)^{-d} \exp\left(i(-kr + \varphi)\right), \tag{5}$$

The effective radius R is fixed and does not depend on the selected degree of damping d. For different degrees of damping capacity in different emitters, the parameter R is constant. Such a requirement is natural for a network that monitors the parameters of the medium with a given spatial resolution.

7.1.2. *Field distribution produced by a system of electric dipole radiators.* A typical cluster size D is assumed to be approximately several metres with a wavelength of $\lambda = 12.5$ cm. Thus, the condition under which the Fraunhofer zone exists is estimated as follows:

$$r \ll D^2/\lambda \tag{6}$$

This study focuses on electric fields at distances smaller than one hundred metres; therefore, complicated interference occurs rather than a polar pattern.

Figure 6 shows the coverage of the three nodes in a virtual antenna array (parameters: $d = 1$ and $\varphi_1 = \varphi_2 = \varphi_3 = 0$) calculated from the amplitude of the electric field intensity spatial distribution produced by synchronously radiating sources. The transmission range of each node is 50 λ, where λ is the wavelength of electromagnetic radiation. The typical frequency range for WSNs is approximately 2.4 GHz. For example, a wireless standard, 802.15.4 (ZigBee), which is designed for use in sensor networks among other applications, has a specification for a given frequency range. If the frequency of the radiation of wireless nodes is 2.4 GHz ($\lambda = 12.5$ cm), the range of nodes is 6.25 m.

The dotted line in Figure 6 corresponds to the transmission range boundary of the three-node system, and the painted area is the size of the field, which exceeds the threshold of

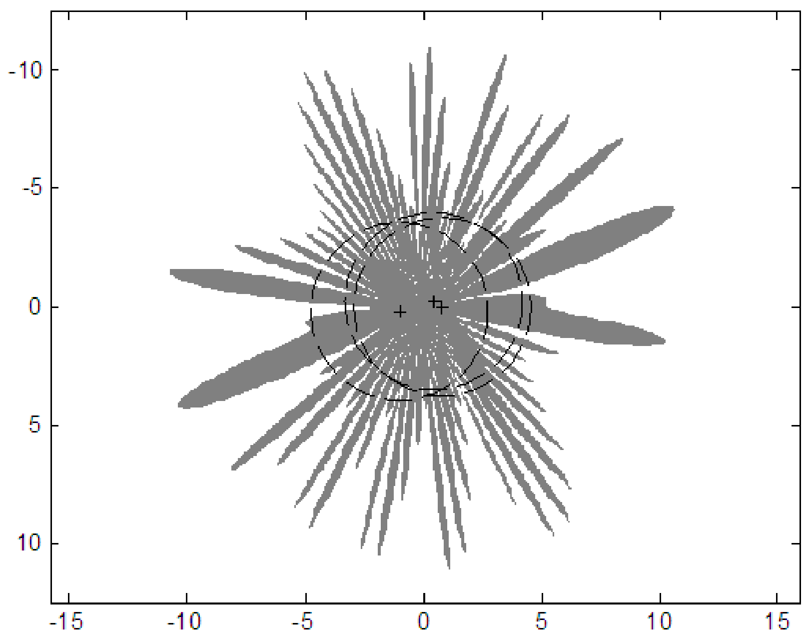

Figure 6. Coverage of a virtual antenna array consisting of three omni-directional antennas

sensitivity E_s. The area of coverage visibly increases compared with the total coverage area of the individual nodes.

Figure 7 shows the coverage of three nodes in a virtual antenna array (parameters: $d = 1$ and the phase (φ) in each node is shifted randomly). The nodes are assumed to transmit a harmonic carrier; the interference pattern can be controlled by changing the phase shift. If the number of nodes in a cluster is greater than two, the interference pattern becomes more complicated. There is no exact dependency between the change of the phase shift and interference pattern. Therefore, an adaptive algorithm for phase shift selection is used in this model.

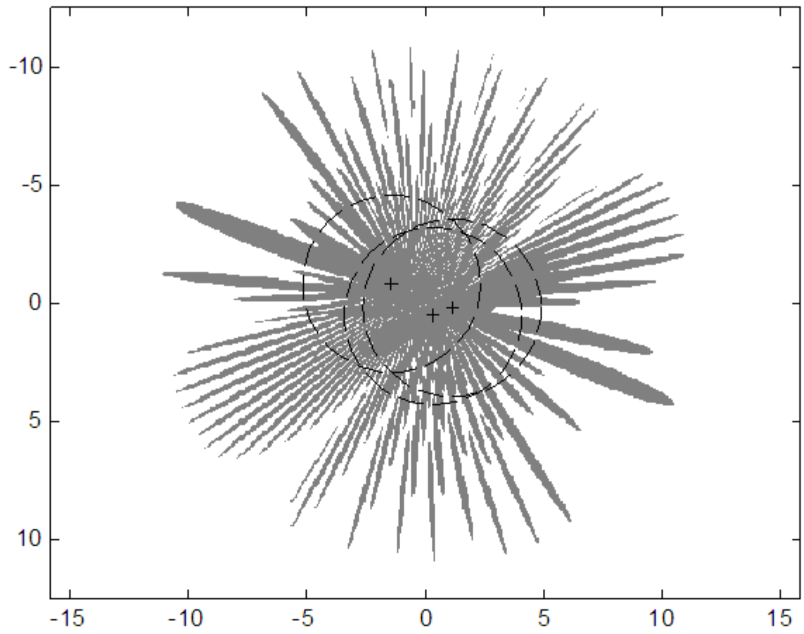

FIGURE 7. Coverage of the virtual antenna array consisting of three omnidirectional antennas using a harmonic carrier

The use of a harmonic carrier is considered to be more effective because the transmission range is significantly increased if the optimal phase distribution in the cluster nodes is found.

7.2. **Clustering algorithm and field of virtual antenna array calculation unit.**

7.2.1. *Distributed clustering algorithm.* The proposed method requires an effective clustering algorithm. A cluster is comprised of nodes close to each other. The concentration of the nodes in a cluster simplifies the data exchange and synchronisation inside the cluster. The clustering algorithm should be energy-efficient because of a limited energy supply. The base of the algorithm is the clustering algorithm, which is described in [29]. The algorithm was improved to achieve a better concentrated cluster organisation and uses the following assumptions:

- Each node has a unique identification number (ID).
- Messages transmitted by each node must be received without errors in a finite period of time.
- The network topology must not change during the session.

TABLE 1. Description of the parts of the algorithm

Part	Description
MNN	*Maximum number of neighbours over its adjacent nodes.*
my_nn	*Number of one hop neighbours of the node that runs the algorithm.*
my_id	*Identification of the node that runs the algorithm.*
my_cid	*Identification of the cluster that this node plans to join or has already joined.*
Γ	*Set of unclustered neighbouring nodes.*
M	*Temporary variable for a set of nodes with maximal MNN used for the condition calculation.*
max_*nn* (Γ)	*Function* Γ *searches for nodes with a maximum number of one hop neighbours and returns the set of nodes.*
min_*id* (Γ)	*Function* Γ *searches for nodes with the minimal id and returns this id. Because the id is a unique number, there can be only one id in the result.*
nn_of (id)	*Function returns the MNN for a cluster with identification id.*
broadcast_cluster (ID, CID)	*Function sends a message to all neighbours of the current node that a node with identification ID has joined the cluster with identification CID.*
set the cluster ID for node ID to CID	*Pseudo function. The current node should remember this.*
on_receiving_cluster(ID, CID)	*Event handler for incoming cluster messages. ID is the identification of the node that joined the cluster, and CID is the identification of the cluster (actual identification of the clusterhead).*

7.2.2. *The parts of the algorithm.* Each node has a dictionary with a key (its own ID and that of its one-hop neighbours) and value (number of neighbours for a corresponding node). This dictionary is called Γ and it contains unclustered neighbours of the current node.

At the start of the algorithm, the dictionary contains all of the neighbours. During algorithm execution, nodes that have already joined the cluster are removed from the dictionary. At the end of the algorithm execution, the dictionary is devoid of all nodes because all nodes have been clustered. Moreover, each node simultaneously runs this algorithm for Γ and broadcasts the message to its one-hop neighbours. The parts of the algorithm are listed and described in Table 1.

7.2.3. *Description of the algorithm.* The clusterization procedure involves the following steps:

- Each node broadcasts its ID to its one-hop neighbours and therefore knows the number of neighbours and their IDs.
- Each node broadcasts the number of its neighbours to adjacent nodes.

Each node forms the table (Γ) with the IDs and number (nn) of neighbouring nodes. Information about the node itself is also given, and each node subsequently executes the distributed clustering algorithm, as described in Figures 8 and 9.

To complete the clusterization procedure, each node (i.e., node number 4 in Figure 10) transmits one message. After clusterization, each node table is supplemented with information regarding the cluster of every neighbouring node. The cluster identification number (CID) is the ID of the node selected to be a clusterhead.

The clusterhead is the node with the maximum number of neighbours among the adjacent nodes. If the number of neighbours is the same for several adjacent nodes, the node with the minimum ID becomes the clusterhead. This algorithm indicates that the maximum route distance between nodes in each cluster is two hops. Therefore, the distance between each node in a cluster and clusterhead is one hop, which is the reason why the clusters are spatially concentrated. For a real-time demonstration of the modified

```
if(my_nn==max_nn(Γ)or(my_id ∈ (M=max_nn(Γ)) and my_id==min_id(M) ))
 {
        my_cid=my_id;
        broadcast_cluster(my_id, my_cid);
        Γ=Γ - my_id;
 }
      for (;;)
        {
          on_receiving_cluster(ID, CID)
        {
        set the cluster ID for node ID to CID;
        if (ID==CID and my_id ∉ Γ and (my_cid==UNKNOWN or nn_of(CID) >
            nn_of(my_cid) or (nn_of(CID) == nn_of(my_cid) and my_cid>CID)))
                {
                    my_cid=CID;
                 }
                     Γ=Γ - ID ;
   if(my_nn==max_nn(Γ)or(my_id ∈ (M=max_nn(Γ))andmy_id==min_id(M) ))
                        {
                          If(my_cid== UNKNOWN
                            {
                                   my_cid=my_id;
                              }
                                     broadcast_cluster(my_id, my_cid);
                                      Γ=Γ - my_id;
                          }
                }
                                         if (Γ==∅)
                                           {
                                                stop;
                                           }
      }
```

Figure 8. Distributed clustering algorithm

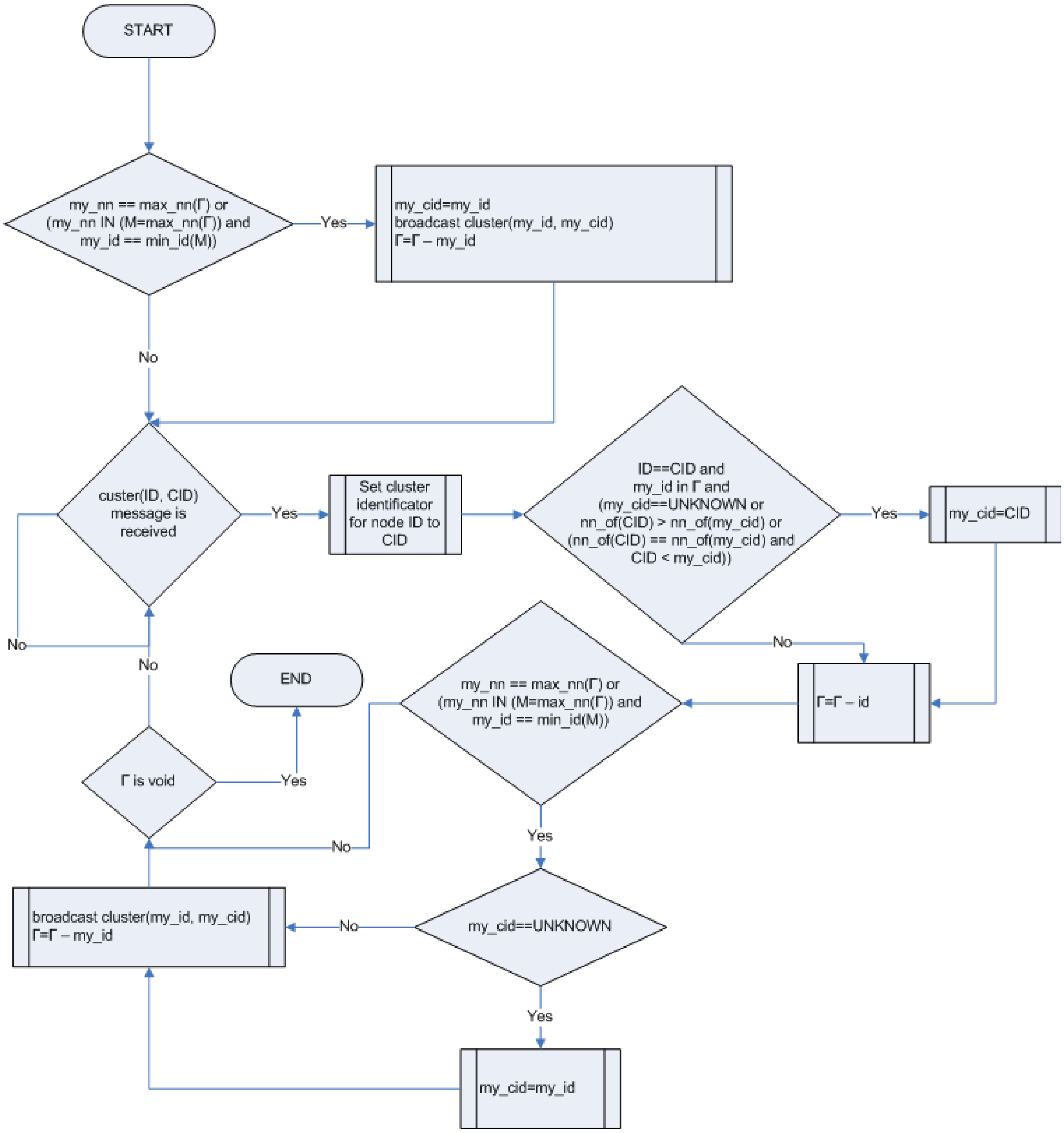

FIGURE 9. Flowchart of the distributed clustering algorithm

clustering algorithm, a model of parallel calculations was performed. Every parallel process represents the behaviour of a single node. Nodes are randomly spread over a specific territory and function using the described algorithm.

The main node (clusterhead) is chosen as the node with the largest number of neighbours (nodes at a distance smaller than R), and nodes 2, 4, and 28 are the chosen clusterheads for their respective clusters (Figure 10). The logic of the algorithm is described as follows:

- An ID exchange between one-hop neighbours occurs;
- Each node broadcasts the number of its one-hop neighbours;
- The node that has the maximum number of one-hop neighbours and minimum ID among several nodes that have the same number of one-hop neighbours is the clusterhead. Upon receipt of the broadcasted message from the clusterhead from one or

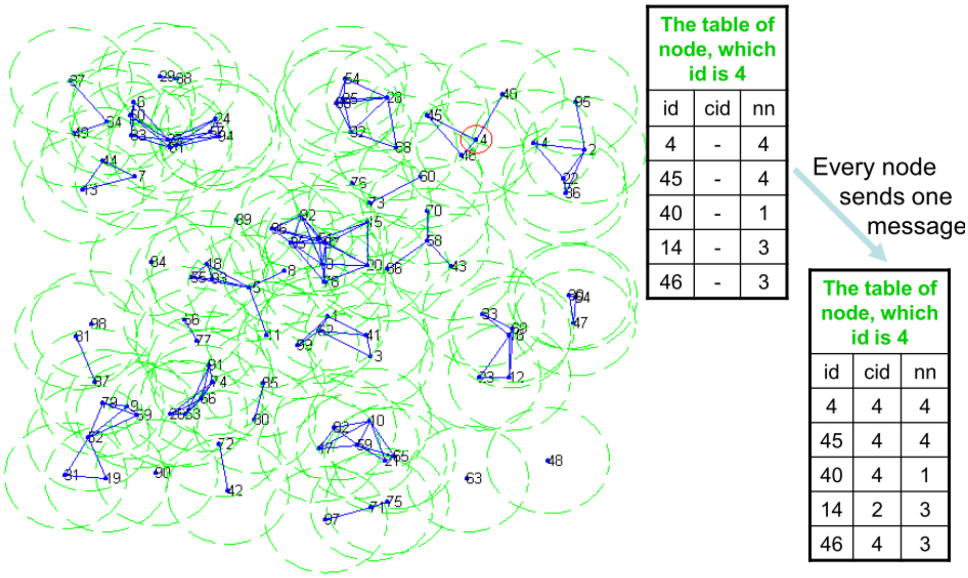

FIGURE 10. Formation table of node number 4

more of its neighbours, other nodes join the cluster (the node with the minimum ID is used in cases where several nodes have the same number of one-hop neighbours).

- A message is broadcast from nodes that are not clusterhead with node ID and ID of clusterhead of its cluster.

Thus, clusterheads that are known to all nodes are included in a cluster. As a result of the algorithm, each cluster has the topology of a star. A connection between the nodes of the cluster occurs through the clusterhead. Direct communication between the clusterhead nodes is absent. Such clusters in fact represent virtual antenna arrays that form the general field of radiation. Clusters, which use an energy-efficient algorithm for the self-organisation of nodes, are formed based on the ID originally assigned to each node [29,30].

This algorithm allows clusters to be obtained in a compact form, which is important for virtual antenna arrays. The node belonging to the cluster allows the transfer of information prior to the distribution phase. Thus, the data between cluster nodes are transferred via a clusterhead node. At the command of the clusterhead node, the information is simultaneously transmitted to any node from all cluster nodes.

The current study assumes that sensor nodes are controlled by a central source. Hence, the locations of each node are known [31].

The distance r between sensors A and B is calculated using the following equation:

$$r(A,B) = \sqrt{|x_B - x_A|^2 + |y_B - y_A|^2} \tag{7}$$

where (x_B, y_B) and (x_A, y_A) are the coordinates of sensors B and A, respectively.

7.3. **Routing algorithm unit.** In the presented network model, the channels are assumed to only exist between a node or cluster and the base station. In addition, the network topology is assumed to be stationary. These assumptions simplify the routing problem.

A new routing algorithm is proposed, which uses the concept of sequential transmission from the cluster with a higher parameter to the cluster with a smaller parameter.

In this algorithm, each node has a parameter characterising the route distance between the node and base station. As the network begins to function, the base station initiates an avalanche-like process that spreads the parameters. The base station has the minimum parameter, whereas its neighbours have the greater parameter. The value of this parameter in each node of the same cluster is similar. The forwarded packets are provided by sequential transmission from a cluster with a higher parameter to a cluster with a smaller parameter.

8. Experimental and Simulation Results.

The relationship between two clusters can be derived from the numerical simulation of the network with MHCTI by adopting bi-directional communication. However, to establish such a relationship, the two clusters should coincide; that is, at least one of the nodes in cluster C should be located within the coverage area of cluster D, and at least one of the nodes in cluster D should be situated inside the coverage area of cluster C.

The abovementioned sensor network is used for the numerical analysis. The simulation experiment is conducted using MATLAB. In the MHCTI simulation, the entire network was segmented into clusters where data transport was facilitated. Network connectivity during the numerical experiments is derived as follows:

$$\varepsilon = \frac{N_c}{N}, \tag{8}$$

where N_c is the number of nodes available for the base station and N is the total number of nodes. The following spatial scales characterise the network: a territory size of $1200\ \lambda \times 1200\ \lambda$, where the nodes are located, and a radius of $30\ \lambda$ for each node. The nodes are dispersed with a non-uniform density. The coordinates of the nodes in each density group are randomly selected, having a uniform distribution function on the grid with a step of $\lambda/2$.

After computing the network connectivity, the number of nodes is increased from 200 to 1600 in steps of 10. The results of the network connectivity calculations and the comparison between the application of MHCTI with parameters $d = 1$ and $d = 2$ with other approaches are shown in Figure 11 [22-24]. As previously discussed, the degree of field attenuation greatly affects the efficiency of the coherent addition of capacity, thus proving the effectiveness of MHCTI in increasing network connectivity. However, to ensure that effective communication is facilitated among all nodes, the number of nodes should be greater than 1100 for $d = 1$ and 1400 for $d = 2$.

Based on Figure 11, of all the included approaches, that of Shuguang et al. [22] most closely resembles MHCTI with $d = 1$. Meanwhile, the approach proposed by Vidhya et al. [24] requires approximately 1600 nodes to guarantee that all nodes can communicate with one another. On the other hand, the method presented by Del Coso et al. [23] substantially reduces network connectivity. Furthermore, a maximum connectivity of 91% was estimated for the network for a maximum of 1600 nodes.

9. Adaptive Algorithm to Adjust the Phase Shifts of Sensor Nodes.

Given that the radius of the single node R is fixed and does not depend on d, the connectivity of the network with other methods [22-24] does not depend on parameter d. Thus, the relationship between the clusters must be bi-directional. When a cluster message is sent, the clusterhead node waits for confirmation from other clusters. Information confirming correct reception can be taken directly to the clusterhead node or to any other nodes in the cluster. The transfer of data is thus initiated by the clusterhead node. If after some period the clusterhead node has not received any confirmation, restructuring phases are implemented in the cluster, and the data are re-transmitted across the cluster. The restructuring phase of radiation randomly occurs in each cluster node. By changing the

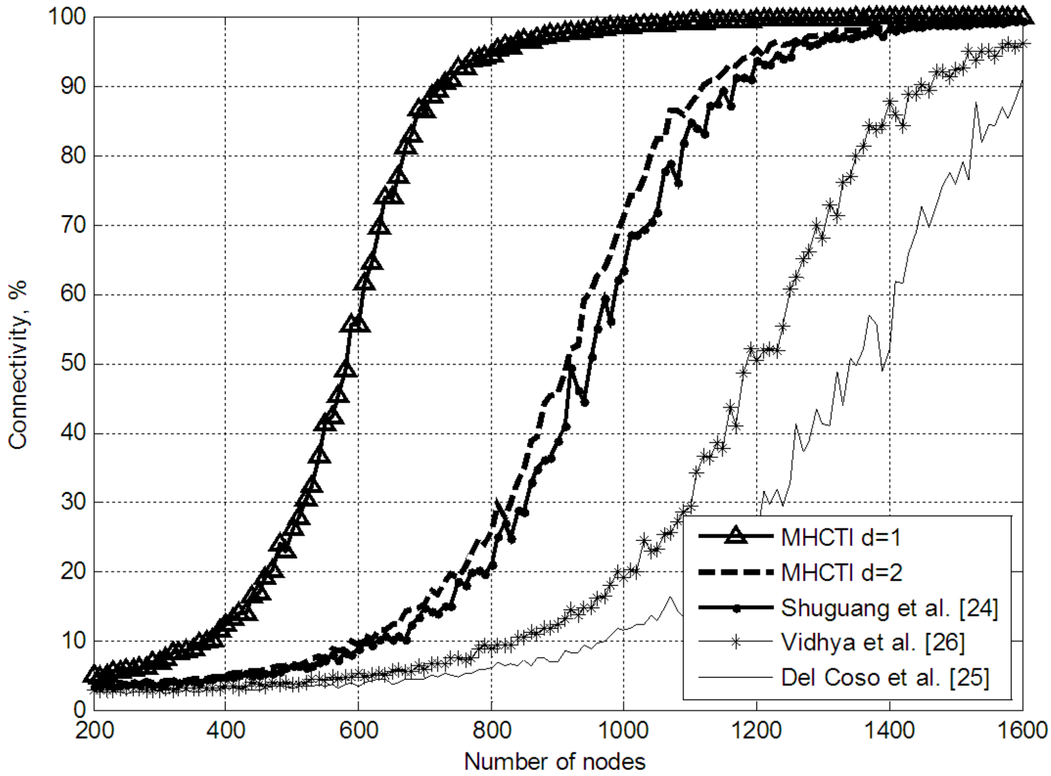

FIGURE 11. The dependence of network connectivity on the total number of nodes

radiation phase in wireless nodes, the zone that covers the sending cluster can be controlled. Implementation of several random restructuring phases enhances the probability of hitting the receiving node in the coverage area of the cluster, which smoothens out the harmful effects of coverage interruption.

The allocation of re-transmitted signals is simplified by using the higher harmonics generated by a non-linear element. For the analysis, we take a thin, perfectly conducting vibrator, which includes a distributed nonlinear load. The Pocklington integral equation [32] can be used to find the currents flowing through the lateral surface of the vibrator on each of the harmonics by obtaining the boundary conditions for the tangential component of the electric field along the axis of the antenna.

A nonlinear load semiconductor diode is chosen by considering the equivalent circuit [33] (Figure 12). The expressions for the currents flowing through the ohmic and capacitive parts of the equivalent circuit (in the case of moderate stress on p-n junctions) are as

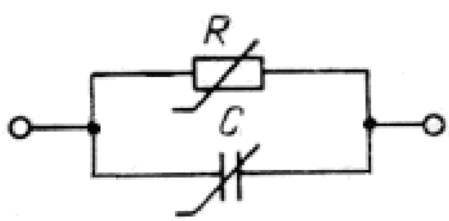

FIGURE 12. Electrical circuit

follows:

$$I_R = I_0\left(e^{\frac{u_0}{m\varphi_T}} - 1\right) + \frac{I_0}{m\varphi_T}e^{\frac{u_0}{m\varphi_T}}(u - u_0) + \frac{I_0}{2(m\varphi_T)^2}e^{\frac{u_0}{m\varphi_T}}(u - u_0)^2,$$
$$I_C = \frac{C_0}{\sqrt{1 - \frac{u_0}{\varphi_Z}}}\frac{\partial u}{\partial t} + \frac{C_0}{2\varphi_Z\left(1 - \frac{u_0}{\varphi_Z}\right)^{3/2}}(u - u_0)\frac{\partial u}{\partial t}, \tag{9}$$

where I_0 is the diode saturation current, $m\varphi_T$ is the temperature transition potential, C_0 is the barrier capacitance at $u = 0$, and φ_Z is the contact potential difference. When analysing the non-linear transformation of the current flowing on the surface of the antenna, we only need to consider the dominant second harmonic component. Using the perturbation method, the current at the fundamental frequency can be estimated using a linear approximation. The second harmonic current can be defined as an amendment, which is introduced by non-linear elements that are connected in parallel to the ohmic resistance of the load and equivalent current generator.

The Pocklington integral equation is solved using the moment method in conjunction with the method of "cross-linking of points" [32]. The current can be represented as the following finite series

$$I(z) = \sum_{n=1}^{N} I_n \cos(2n - 1)\frac{\pi \cdot z}{L}, \tag{10}$$

which defines the unknown I_n as a system of linear algebraic equations.

The parameters of the diode can be modulated by changing the offset operating point, u_0'. The receiving point in the far field samples the analogue-phase modulation. The simulation results show that the near-resonant antenna lengths and moderate amplitude offset (-5 V$< u_0 < 0$ V) phase response of the modulated field are almost linear, which results in good detection accuracy despite significant non-linear amplitude distortions.

Figures 13 and 14 show the amplitude and phase, respectively, of the second harmonic field at the receiving point for the harmonic changes of the bias voltage within -3 V-0 V with a frequency of 200 Hz. Here, the amplitude and phase shift keying are parameters that affect the signal immunity distance.

Figure 15 shows an example of the hodograph of the E vector for u_0 and constellation diagram for two signals. Studies have shown that by choosing the parameters of the non-linearity and length of the antenna, the signal amplitude can achieve values of 8×10^{-4} V/m for second harmonic field amplitudes of $\sim 10^{-3}$ V/m and a phase of $\sim \Delta\varphi 154°$.

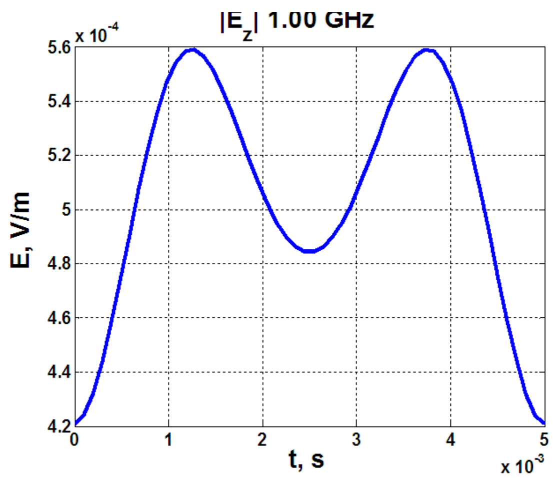

FIGURE 13. Amplitude of the second harmonic field at the receiving point

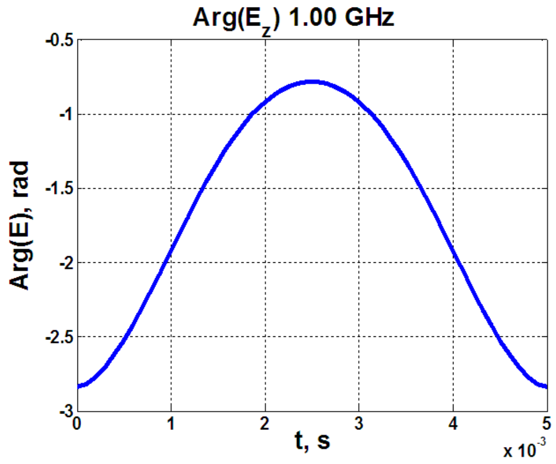

FIGURE 14. Phase of the second harmonic field at the receiving point

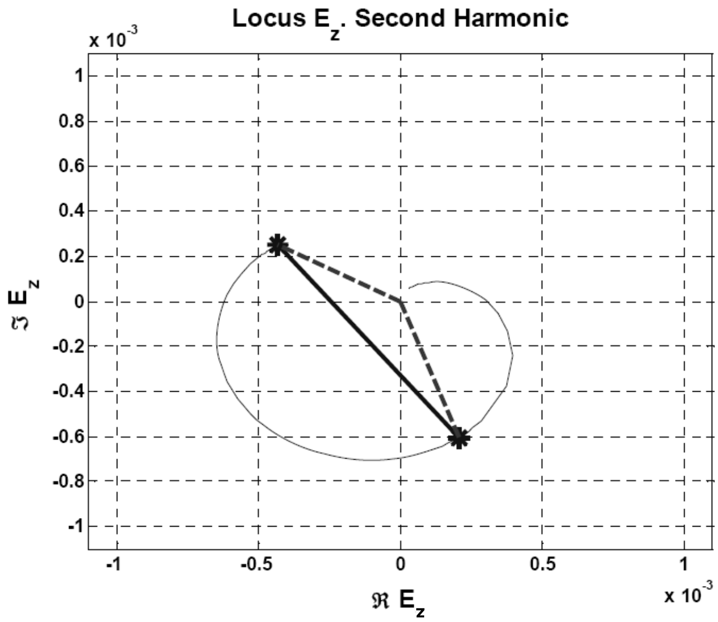

FIGURE 15. Hodograph of the E vector

As shown in Figure 15, a non-linear dipole antenna with a reactive load can be used as a controlled phase shifter.

Figure 16 shows the improved connectivity of a network when $d = 1$ and $d = 2$ using a simple adaptive algorithm for the random selection of phase shifts. In this case, each node of the cluster has a maximum of four random changes. Here, even a random selection of phase shifts using the MHCTI method qualitatively improves network connectivity.

10. **Lifetime of Network.** An analysis of the lifetime of sensor networks with non-uniform density is presented. In a typical sensor network, the base station collects all the data transmitted by the nodes, providing storage of relevant information and access to other networks (e.g., the Internet).

The base station is the point where all obtained data from non-uniform density sensor networks are converged. Hence, the nodes with the closest proximity to the base station are assigned with the maximum power load. Energy degradation primarily occurs in these

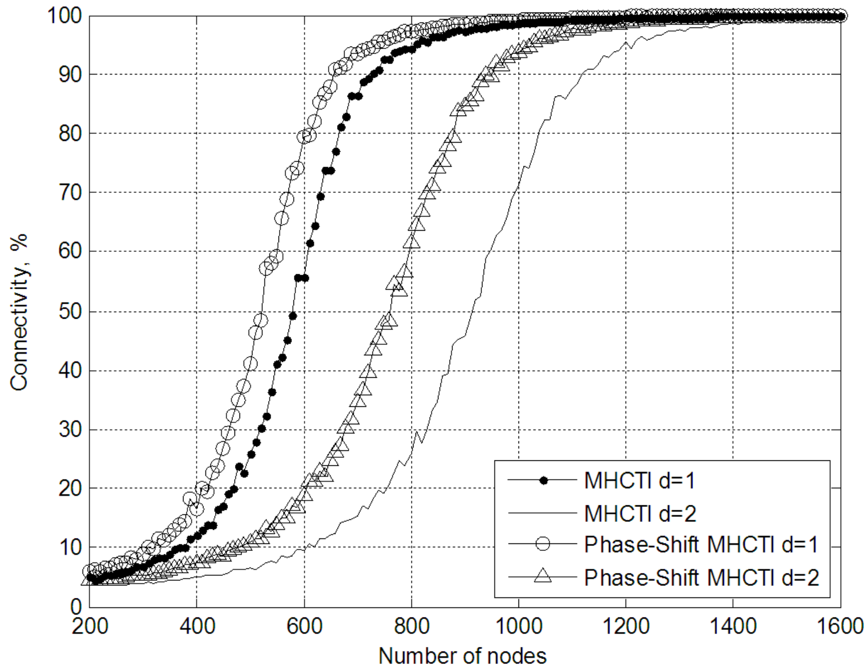

Figure 16. The dependence of network connectivity on the total number of nodes with and without random phase shift selection

nodes; hence, if the base station is separated from all other sensor nodes, an unused energy resource is retained.

Figure 17 illustrates the degradation of energy in the sensor networks with non-uniform density, with and without the MHCTI method [22-24]. A total of 200 nodes were situated within a territory size of 100 m × 100 m. The network connectivity is based on the number of surveys online. Hence, "connectedness" refers to the relative number of nodes (in percent) or data transported to the base station. The success or failure of the nodes located near the base station determines the delivery of information. After a number of cycles, the number of sensor nodes decreases, the evidence of which are as follows: (a) Del Coso et al. [23], after 21 network cycles; (b) Vidhya et al. [24], after 27 network cycles; and (c) Shuguang et al. [22], after 32 network cycles. On the other hand, with the MHCTI method, approximately 50 network cycles were performed before a decrease in the number of sensor nodes is observed.

Figure 17 also presents the degree of attenuation of the field $d = 1$ for non-uniform density sensor networks. An initial energy reserve of 0.5 J was assigned to each node. In the experiment, information was periodically transmitted to the base station, that is, a broadcast request is sent by the base station, after which information from all the nodes is transmitted. This process of data transmission is called a network scan. Energy is needed to perform the preliminary exchange of data within the cluster, as well as the collective data transfer from all cluster nodes; hence, energy consumption was considered. The energy spent for sensory data can be determined because the transmission radius of all nodes is fixed. To determine how much energy is consumed during the reception and transmission of one message from one node to another, the following formula is adopted:

$$E_{Relay(x)} = E_{Trans(x,r)} + E_{Receiv(x)}, \tag{11}$$

where

$$E_{Trans(x,r)} = E_{elec} \times x + (\varepsilon_{amp} \times x \times r^2), \tag{12}$$

and

$$E_{Receiv(x)} = E_{elec} \times x, \tag{13}$$

In these formulas, $E_{Receiv(x)}$ and $E_{Trans(x,r)}$ refer to the energy required to receive and transmit x bits over r metres, respectively; E_{elec} is a constant that represents the power required for information processing, and ε_{amp} is the power amplification constant. The parameters were set as follows: $E_{elec} = 50$ nJ/bit, $\varepsilon_{amp} = 100$ pJ/bit/m^2, and $x = 2000$ bits. Equations (12) and (13) were derived from [34]. As implied by the results of the computer simulation (Figure 17), the MHCTI method minimises the observed energy degradation in the network compared with the other methods.

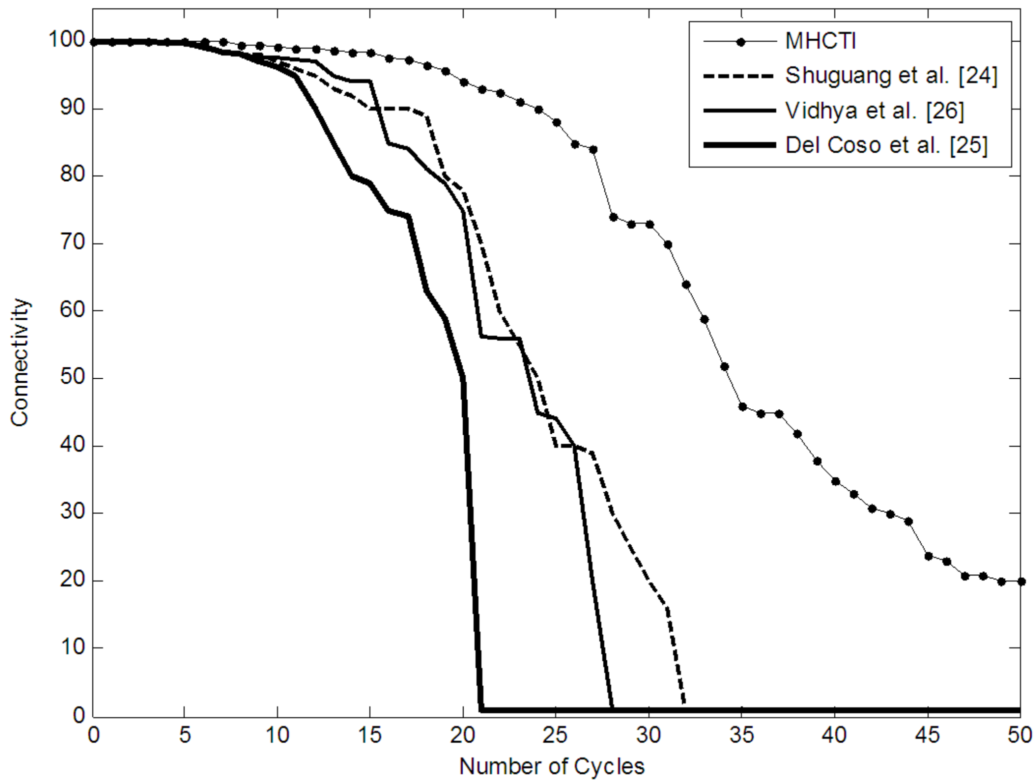

FIGURE 17. Energy degradation of a non-uniform density sensor network using the MHCTI method and other conventional approaches

11. **Conclusion.** This study proposed and evaluated the effectiveness of the coherent addition of nearby nodes in a sensor network for the joint transmission of information based on the cluster approach. Computer simulations showed that the connectivity of the network is improved using the MHCTI method compared with previously described methods. This finding is most evident when the degree of attenuation of the electromagnetic field is $d = 1$. To improve network connectivity and facilitate random phases in the tuning of the emitter, a simple adaptive algorithm was applied. A zone-fading signal was observed in the actual condition of multi-path propagation nodes, resulting in communication disruptions. To effectively address similar interference effects, the radiation field of the cluster was controlled by changing the phases in the transmitter. Thus, the lifetime of the sensor network is effectively extended using the MHCTI method. However, further research is needed to study transmission synchronisation within clusters.

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