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Full Length Research Paper

Interference reduction in mobile ad hoc and sensor networks

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There are still a lot of open questions in the field of mobile ad hoc networks (MANETs) and sensor networks. If a topology incurs a large interference, either many communication signals sent by nodes will collide, or the network may experience a serious delay at delivering the data for some nodes, and even consume more energy. So, we reach the conclusion that interference imposes a potential negative impact on the performance of wireless networks. In the last few years, researchers actively explored topology control approaches for such networks. The motivation of topology control (TC) is to maintain the connectivity of the network, reduce the node degree and thereby reduce the interference, and reduce power consumption in the sensor nodes. Some literatures have pointed out that a node can interfere with another node even if it is beyond its communication range. To improve the network performance, designing topology control algorithms with consideration of interference is imminent and necessary. Since, it leads to fewer collisions and packet retransmissions, which indirectly reduces the power consumption and extends the lifetime of the network. In this paper, we propose a new interference-aware connected dominating set-based (IACDS) topology construction algorithm, namely, IACDS algorithm, a simple, distributed, interference-aware and energy-efficient topology construction mechanism that finds a sub-optimal connected dominating set (CDS) to turn unnecessary nodes off while keeping the network connected and providing complete communication coverage with minimum interference. IACDS algorithm utilizes a weighted distance-energy-interference-based metric that permits the network operator to trade off the lengths of the branches (distance) for the robustness and durability of the topology (energy and interference).

Key words: Interference, mobile ad hoc networks (MANETs), topology control, connected dominating set (CDS), wireless sensor network (WSN), interference-aware connected dominating set-based (IACDS) algorithm.

INTRODUCTION

A mobile ad hoc network (MANET) is a temporary self-organizing multi-hop system of wireless mobile nodes which rely on each other to keep the network connected without the help of any preexisting infrastructure, pre-defined topology, or central administrator. These networks are generally formed in environments where it is difficult to find or settle down a network infrastructure Santi (2005). In this type of networks, nodes must collaborate and organize themselves to offer both basic network services as routing and management services as security. A wireless sensor network (WSNs) is a wireless network consisting of spatially distributed autonomous devices using sensors to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion, or pollutants, at different locations (Roemer et al., 2004; Westhoff et al., 2006).

Wireless sensor networks (WSNs) are a particular type of ad hoc networks, in which the nodes are sensors equipped with wireless transmission capability. Hence, they have the characteristics, requirements, and limitations of an ad hoc network (Santi, 2005). The term ad hoc network describes a type of wireless network without a fixed infrastructure. Conventional wireless networks including WiFi and cellular networks have supporting backbones and are hierarchical. Nodes communicate with each other via the base stations. In an ad hoc network the nodes can communicate with each other directly via multi-hops paths. Usually the network

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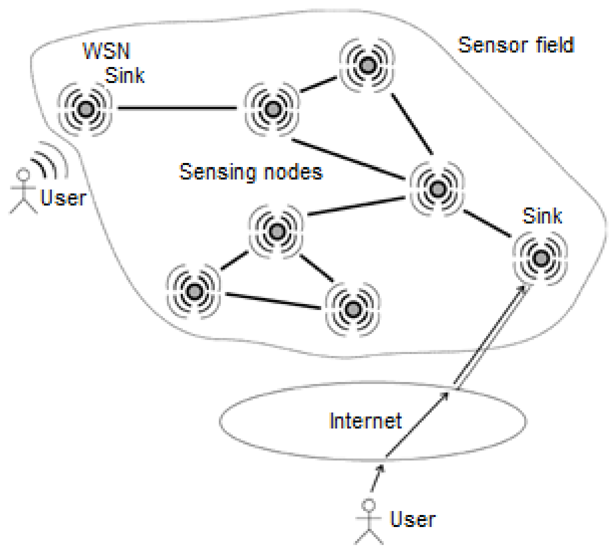

Figure 1. Basic structure of a wireless sensor network.

does not have any coordinating node and hence, ad hoc networks are decentralized, self-organized, and self-healing. Messages may be duplicated on the way to the base station to provide extra resilience (Akyildiz et al., 2002).

A WSN is usually composed of a large number of sensing nodes in the order of tens, hundreds, or even thousands scattered in a sensor field and one or a few base stations/ sinks, which connect the sensor networks to the users via the internet or other networks. Sensor nodes are equipped with sensing, data processing, and communicating components to accomplish their tasks. Each of the sensor nodes is capable of collecting data and routing the data back to the sink by multi-hopping, as illustrated in Figure 1.

Interference in MANETs and sensor networks

One of the main challenges of wireless communication is interference. Unfortunately, research in this area is so young that researchers have to investigate different ideas regarding the identification of a universal measure of network interference. According to the Glossary of Telecommunication Terms - Federal Standard 1037C, interference is defined as a coherent emission having a relatively narrow spectral content, for example, a radio emission from another transmitter at approximately the same frequency, or having a harmonic frequency approximately the same as another emission of interest to a given recipient, and which impedes reception of the desired signal by the intended recipient.

Informally speaking, a node u may interfere with another node v if u's interference range unintentionally covers v. Consequently, the amount of interference experienced by a node v corresponds to the amount of interference produced by nodes whose transmission range covers v.

Interference reduction in MANETs and sensor networks

In frequency division multiplexing cellular networks, reducing the amount of interference results in fewer channels, which in turn, can be exploited to increase the bandwidth per frequency channel. In systems using code division multiplexing, small interference helps in reducing coding overhead. In the context of ad hoc and sensor networks, there is an additional motivation for keeping interference low. In these networks consisting of battery driven devices, energy is typically scarce and the frugal usage of it is critical in order to prolong system operability and network lifetime. In addition to enhancing throughput, minimizing interference may help in lowering node energy dissipation by reducing the number of collisions (or amount of energy spent in an effort of avoiding them) and consequently retransmissions on the media access layer.

Interference can be reduced by having nodes send with less transmission power. The area covered by the smaller transmission range will contain fewer nodes, yielding less interference. On the other hand, reducing the transmission range has the consequence of communication links being dropped. However, there is surely a limit to how much the transmission power can be decreased. In ad hoc networks, if the node's transmission ranges become too small and too many links are abandoned, the network may become disconnected. Hence, transmission ranges must be assigned to nodes in such a way that the desired global network properties are maintained.

Topology control

Topology control (TC) is one of the most important techniques used in wireless ad hoc and sensor networks to reduce energy consumption (which is essential to extend the network operational time) and radio interference (with a positive effect on the network traffic carrying capacity). The goal of this technique is to control the topology of the graph representing the communication links between network nodes with the purpose of maintaining some global graph property (for example, connectivity), while reducing energy consumption and/or interference that are strictly related to the nodes' transmitting range. An informal definition of topology control is the art of coordinating nodes, decisions regarding their transmitting ranges, in order to generate a network with the desired properties. Interference-efficient topology control is to find a sub-graph H from the original graph G, representing a network, to minimize interference while preserving fixed properties (connectivity and low power consumption). Topology control is a system-level perspective to optimize the choice of the nodes' transmit power levels to achieve a certain global property while power control is a wireless channel perspective to optimize the choice of the transmit power level for a single wireless transmission, possibly along several hops.

Topology control techniques have the potential to mitigate two important problems occurring in wireless ad hoc networks: node energy consumption and radio interference.

Another major requirement of topology control in MANETs and sensor networks is to maintain connectivity in the network. Once the connectivity is ensured, the second goal is usually to reduce the radio transmission power of individual nodes for two reasons. The first is to reduce the power used for transmitting packets. The second one is to reduce the node degree in the neighborhood. A sparse network is desirable because it can enhance the performance of the MAC protocols. If a CSMA type scheme is used, low network degree means less probability of collisions. If a TDMA scheme is used, slot assignment is easier with fewer nodes and there is less chance of congestion. Moreover, routing is simpler in a sparse network than a dense network because there are fewer routes to consider.

RELATED WORKS

Topology control

Topology construction can be exercised by reducing the transmission range of all nodes by the same minimum amount, or the minimum transmission range for each node (Santi, 2005). Other techniques are based on the assumption that nodes have information about their own positions and the position of their neighbors (Li et al., 2001), or that they have directional antennas that are used to determine the orientation of the nodes (Kumar et al., 2002; Li et al., 2003). Although both assumptions are valid, they are costly and not easy to implement. Other topology control methods, such as the one considered in this paper, are based on the connected dominating set (CDS) paradigm. Here, the idea is not to change the transmission range of the nodes but to turn unnecessary nodes off while preserving important network properties, such as connectivity and communication coverage.

The CDS approach has been utilized in several papers (Kumar et al., 2002; Butenko et al., 2004; Chen et al., 2002; Guha and Khuller, 1998; Wu et al., 1999, 2004, 2006; Yuanyuan et al., 2006). Most CDS-based mechanisms work in two phases: In phase one, they create a preliminary version of the CDS, and in phase two they add or remove nodes from it to obtain a better approximation to the optimal CDS. Two relevant CDS-based mechanisms are the energy efficient CDS (EECDS) (Wu et al., 1999) and the CDS-Rule-K (Guha and Khuller, 1998) algorithms.

The EECDS algorithm builds a CDS tree creating maximal independent sets (MIS), which are clusters with non-connected clusterheads, and then selects gateway nodes to connect the clusterheads of the independent sets. The EECDS algorithm proceeds in two phases. The first phase begins with an initiator node that elects itself as a clusterhead and announces it to its neighborhood. This set of nodes is now "covered". The now "covered" nodes will pass the message to its uncovered neighbors, 2-hop away from the initiator, which start competing to become clusterheads. Once there is a new clusterhead, the process repeats with the 4-hop away nodes from the initiator, until there are no more uncovered nodes. On the second phase the covered non-clusterhead nodes compete to become gateways between the clusterheads.

The CDS-Rule-K `utilizes the marking algorithm proposed in Wu et al. (1999) and the pruning rule included in Wu et al. (2004). The idea is to start from a big set of nodes that accomplishes a minimum criterion and prune it according to a specific rule. In the first phase, the nodes will exchange their neighbor lists. A node will remain active if there is at least one pair of unconnected neighbors. In the second phase, a node decides to unmark itself if it determines that all its neighbors are covered by marked nodes with higher priority, which is given by the level of the node in the tree: lower level, higher priority. The final tree is a pruned version of the initial one with all redundant nodes with higher or equal priority removed.

Interference reduction via topology control

Here, related works in the field of topology control are discussed with special focus on the issue of interference. Interference reduction is one of the main motivations of topology control besides direct energy conservation by restriction of transmission power. Astonishingly however, all the above topology control algorithms at the most implicitly try to reduce interference. Where interference is mentioned as an issue at all, it is maintained to be confined at a low level as a consequence to sparseness or low degree of the resulting topology graph.

However, Burkhart et al. (2004) reveal that such an implicit notion of interference is not sufficient to reduce interference since message transmission can affect nodes even if they are not direct neighbors of the sending node in the resulting topology. Besides demonstrating the weakness of modeling interference implicitly, Burkhart et al. (2004) introduces an explicit definition for interference in wireless networks. Burkhart et al. (2004) presents a traffic-independent model and defines the interference of a link e = (u, v) as the cardinality of the set of nodes covered by two disks centers at u and v with radius ||uv||, denoted as coverage set of link e, cov(e). This model, named as link-interference via coverage, is chosen from the assumption that whenever a link (u, v) is used for a send-receive transaction all nodes whose distance to node u or node v is less than ||uv|| will be affected in some way.

Moaveni et al. (2005), extend this work and propose node-interference via coverage model. The interference of a node u is defined as the maximum coverage set of links incident on u. However, coverage model is based on the question how many other nodes can be disturbed by a given communication node or link. The definition of interference suggested in Moaveni et al. (2005) is problematic in two respects. First, it is based on the number of nodes affected by communication over a given link. In other words, interference is considered to be an issue at the sender instead of at the receiver, where message collisions actually prevent proper reception. It can therefore be argued that such sender-centric perspective hardly reflects real-world interference. The second weakness of the model introduced in Moaveni et al. (2005) is of more technical nature. According to its definition of interference, adding (or removing) a single node to a given network can dramatically influence the interference measure. Addition of one node to a cluster of roughly homogeneously distributed nodes entails the construction of a communication link covering all nodes in the network, accordingly - merely by introduction of one additional node - the interference value of resulting topology is pushed up from a small constant to the maximum possible value, that is the number of nodes in the network. This behavior contrasts to the intuition that a single additional node also represents one additional packet source potentially causing collisions. Moreover, neglect of the case that a particular node might be influenced by multiple communication links with small coverage set might lead discontented results of the proposed algorithms in Moaveni et al. (2005).

An attempt to correct this deficiency is made by Richenband et al. (2005), where an alternative, receiver-centric, interference model is introduced. In this model, node u will be interfered by v whose distance to v is less than Rv, its distance to reach the farthest neighbor, or {v | ||uv|| ≤ Rv} formally. It is denoted as node-interference via transmission model. Under the assumption that only symmetric edges are considered, it can be proved that nodes set, mentioned earlier, is equivalent to {v | ||uv|| ≤ Ru}. Unfortunately, one fatal drawback is that previous works consider the interference range equals to the transmission range. According to the theoretical analysis of actual cause of interference by Xu et al. (2003), interference range generally differs from transmission range and hidden terminals located within the 1.78d distance (d denotes the communication distance) of the receiver are also disturbing sources, which is neglected in previous works at all times. Researches mistake nodes within the transmission range for the only hidden interfering nodes.

Authors of Meyer et al. (2002) introduce an explicit definition of interference between edges and establish – based on a time-step routing model – a trade-offs between the concepts of congestion, energy consumption, and dilation. This interference definition is based on the current network traffic. In Meyer et al. (2002), more attention is also being paid to the fact that if nodes are capable of adapting their transmission power – an assumption already made in early work that can be considered originators of topology control considerations (Hou et al., 1986; Takagi et al., 1984) – interference ranges correlate with the length of communication links. More precisely the interference range of a link depends on the transmission power levels chosen by the two nodes communicating over the respective link. While Meyer et al. (2002) defines interference based on current network traffic, Burkhart et al. (2004) introduces a traffic-independent notion of interference. Moreover, the latter work shows that the previous statement that graph sparseness or small degree implies low interference is misleading. The interference model described in Burkhart et al. (2004) builds on the question of how many nodes are affected by communication over a given link. This sender-centric perspective can however be accused to be somewhat artificial and to poorly represent reality, interference occurring at the intended receiver of a message. Furthermore, this interference measure is susceptible to drastic changes even if single nodes are added to or removed from a network.

PROPOSED SOLUTION

Interference-efficient topology control is to find a sub-graph H from the original graph G to minimize interference while preserving fixed properties.

Network representation

An ad hoc network is modeled as an Euclidian graph G = (V, E) with vertices in V representing network nodes, and the edges E representing communication links. The Euclidian position of the vertices in the graph corresponds to the physical position of the nodes in the Euclidian two dimensional space, which means that the edge weight, w(u, v), represents the physical distance between nodes u and v. Each node u has a maximum transmission range Ru. In order to prevent existing basic communication between neighboring nodes from becoming unacceptably cumbersome (Prakash, 1999), only symmetric edges are considered. Since only undirected links are considered, a link uv can only exist if the Euclidian distance between the nodes u and v is no larger than min (Ru, Rv). Assume that any node can adjust its transmission power to any value from 0 to its maximum transmission power, depending on the desired

Algorithm 1.

Algorithm 1
Purpose: Calculating the interference amount at the receiver of HM
Inputs: Hello Message HM
Outputs: Total interference amount IA(receiver)

Procedure:

1. For (i=1 to numberOfNeighbors) {
a. IR = 1.78 * d (receiver, Neighbors (i))
b. INS (i) = 0
c. For (j=1 to numberOfNeighbors) {
i. If (d (receiver, Neighbors (j)) ≤ IR)
ii. INS (i) ++
d. }
2. }
3. IA (receiver) = max $\mathrm{INS_i}$

Where:
IR refers to Interference Range
d refers to the Euclidean distance
INS refers to Interference Neighbor Set
IA refers to Interference Amount

transmission radius: when transmitting to node v, node u uses the lowest possible transmission power needed to reach v. A common path loss model says that the signal strength received by a node can be described as p/dα, where p is the transmission power used by the sending node, d is the distance between two nodes, and α is a path loss gradient, depending on the transmission environment. Consequently, the energy cost c(u, v) to send a message of fixed length directly from node u to node v is θ(|u, v|α). The energy cost of a path is defined as the sum of the energy costs of all edges in the path.

Measurement of interference

Intuitionally, a node in the network G is interfered by others, if messages are received but not intended for it (Zhang et al., 2007). From the perspective of the physical layer, a signal arriving at a receiver is assumed to be valid if the signal to noise ratio (SNR) is above a certain threshold TSNR. Assume a transmission to a receiver with transmitter-receiver d meters apart and at the same time, an interfering node d meters away from the receiver starts another transmission. According to analysis in Xu et al. (2003), a crucial conclusion is made that interference range is $\sqrt[4]{T_{SNR}} * d$, with an approximation value of 1.78*d when TSINR is set to 10 for instance. Previous researchers mistake nodes within the transmission range for the only hidden interfering ones. Distinctly, for a node, all active neighbors within its interference range are potential interfering sources. Consequently, interference amount is defined as the maximum cardinality of active interference neighbors set. Given a network N = (V, E), the interference neighbors set of a node u communicating with v in N, denoted as INS_u^v, is defined as follows:

$$INS_u^v = \{w \in V \mid w \in D(w, \sqrt[4]{T_{SNR}} * \|uv\|)\} \quad (1)$$

Consequently, the interference amount of the node is defined as:

$$\text{IA (receiver)} = \max \mathrm{INS_i} \quad (2)$$

Where D (u, r) denotes the set of nodes located in the circular area centered at node u with radius r, and ||uv|| the communication distance.
The receiver node of a “Hello Message” computes its interference amount using Algorithm 1.
Figure 2 shows an example network consisting of twenty nodes. The interference neighbor set of node u when communicating with node v is seven, while its interference neighbor set when communicating with node w is eleven, and when communicating with node z its interference neighbor set equals to ten. The maximum of its interference amounts is 11. Based on the previous definition node u suffers from interference, and it can be measured as follows:

$$INS_u^v = 7 \quad (3)$$

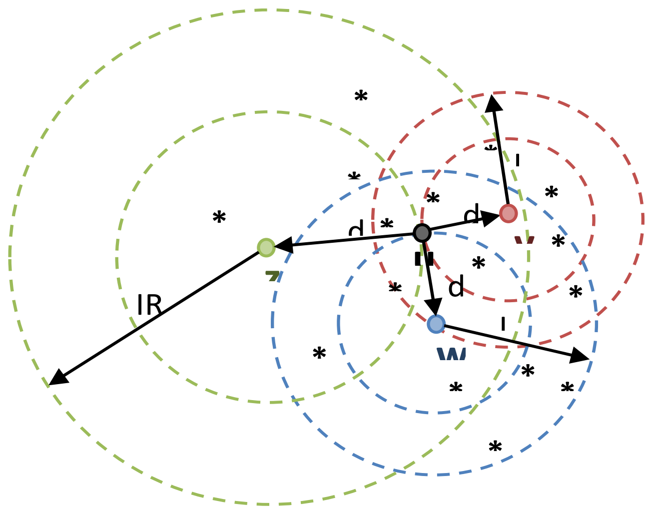

Figure 2. Example network to demonstrate the first interference metric.

$$INS_u^w = 11 \quad (4)$$

$$INS_u^z = 10 \quad (5)$$

$$I(u) = \max_{x=v,w,z} INS_u^x \quad (6)$$

$$I(u) = INS_u^w = 11 \quad (7)$$

The previous definition is problematic, since it works according to the principle: The global interference in a network depends solely on the local part with the highest interference. Reducing the interference in that part by definition reduces the interference of the entire network. One problem is that the metric does not consider the interference in general; a network with high interference in one place and low interference everywhere else could have the same interference as another network with equally high interference everywhere. We extend the previous work by defining an average interference neighbors set as the sum of the interference neighbors sets divided by the number of neighbors.

$$IA(receiver) = \sum_{i=1}^{|INS|} INS_i / |INS| \quad (8)$$

Despite the previous extended metric makes a relationship between all local parts of the network, from another point of view it suffers from some weakness: it does not take into account the real distribution of the interference in the network, which means that several networks with different interference amounts in their local parts may have the same global interference. In other words, there will be local parts with higher interference than the global interference of the entire network which is not realistic, for example, a network with high interference in one place and low interference everywhere else.

We propose to form an interference measure which functions with the following properties: creates a relationship between all local parts of the network, and takes into account the maximum interference of the network. This can be achieved by mixing the previous two metrics in one equation.

$$IA(receiver) = \sum_{i=1}^{|INS|} INS_i / |INS| * \max INS_{i=1}^{|INS|} \quad (9)$$

INTERFERENCE-AWARE CDS-BASED TOPOLOGY CONSTRUCTION ALGORITHM (IACDS)

Topology control is a well-known strategy to save energy and extend the lifetime of wireless mobile ad hoc and sensor networks. In this paper we exploit the benefits of topology control in order to reduce interference in the entire network. So, we propose the IACDS algorithm, a simple, distributed, and energy-efficient topology construction mechanism that finds a sub-optimal connected dominating set (CDS) to turn unnecessary nodes off while keeping the network connected and providing complete communication coverage with minimum interference. IACDS algorithm utilizes a weighted distance-energy-interference-based metric that permits the network operator to trade off the lengths of the branches (distance) for the robustness and durability of the tree (energy and interference).

IACDS algorithm

Interference-efficient topology control is to find a sub-graph H from the original graph G to minimize

Algorithm 2.

Algorithm 2
Purpose: CDS topology such that the resulting topology is connected and with minimal interference. *Inputs: Original network G =(V, E)* *Outputs:* $H_{CDS}=(V_H, E_H)$
Procedure: *1.* $V_H = \{sink\}$ *2. Start with the sink node: discover its neighborhood NH* *3. For each node* $\mathbf{v} \in NH$*, calculate the interference metric* *4. Sort nodes in NH in an ascending order of the interference metric* *5. While NH is not empty* *6. Select* $\mathbf{v} \in NH$ *with minimum interference metric and outside the coverage area of other node in the neighborhood* *- if sink and* ***v*** *are not connected in* H_{CDS} *then* $V_H = V_H \cup \{\mathbf{v}\}$ *- end if* *-* $NH = NH \setminus \{v\}$ *7. End while* *8. Repeat step 2 with all* ***v****'s in* V_H *9.* $H_{CDS} = (V_H, E_H)$

Table 1. Simulation parameters.

Parameter	Simulation 1	Simulation 2	Simulation 3
Deployment area		200 × 200 m	
Number of nodes	100	10, 20, 40, 60, 80, 100	36, 64
Transmission range	28, 42, 56, 70, 84 m	63 m	40 m
Node distribution	Uniform (200, 200)		Grid HV and Grid HVD
Instances per topology		50 instances	
Maximum energy		1 Joule	
IACDS weights		WI = 0.5, WE = 0.5, WD = 0.5	

interference while preserving fixed properties (connectivity and low power consumption) (Algorithm 2).

SIMULATION RESULTS

The following assumptions were made during the simulation:

(1) Nodes are located in a two dimensional space and have a perfect communication coverage disk.
(2) The initial graph is connected.
(3) Distances can be calculated as a metric perfectly proportional to the received signal strength indicator (RSSI).
(4) Idle state energy consumption is assumed negligible.
The networks are constructed by uniformly distributing nodes in a 200 × 200 square area. Without loss of generality, the mean result is derived from 50 networks randomly generated with a fixed number of nodes and different transmission ranges for the first simulation (changing the node degree) and different number of nodes and fixed transmission range for the second one (changing the node density). Table 1 presents a summary of the simulation parameters used in the performance evaluation of the proposed interference reduction mechanism.

Simulation 1: Changing the node degree

This simulation mainly aims to compare the algorithms when the node degree of the network is changed by increasing the transmission range of the nodes while

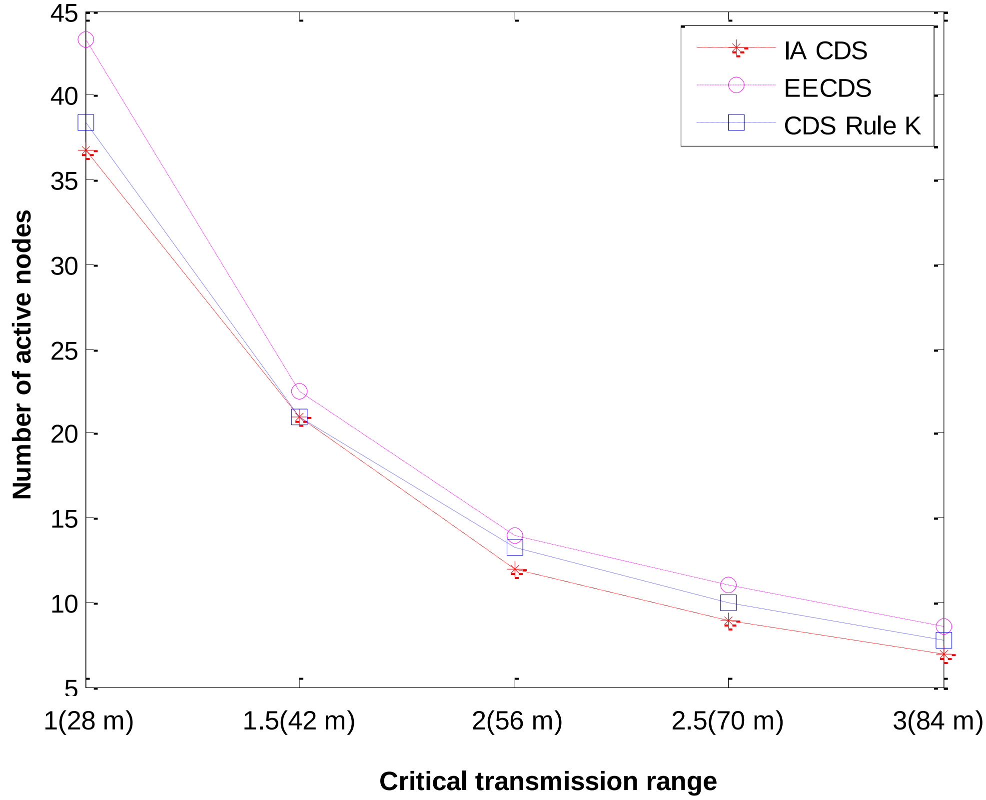

Figure 3. Number of active nodes versus transmission range of the nodes.

maintaining the number of nodes fixed = 100. Given that these algorithms work based on information from neighbors, it is important to measure their performance with neighborhoods of different sizes.

As it can be seen from Figure 3, the three algorithms produce CDSs with almost similar number of nodes. However, IACDS generates fewer nodes in all scenarios. Another note to be seen from this figure, all the algorithms tend to decrease the number of active nodes with the node degree, as expected.

Figures 4 and 5 show two important metrics: the total energy and number of messages used to build the CDSs. In this case, the IACDS mechanism shows its superior performance. IACDS presents an almost constant energy consumption and number of messages compared with the EECDS and CDS-Rule-K algorithms, which show a non-linear increase trend. These results can be easily explained.

The non-linear behavior of the EECDS mechanism is explained by the competition used in both phases of the algorithm. This is due to the fact that with a higher communication range, more nodes are covered, and the network has fewer nodes in higher levels. This, at the same time, reduces the amount of nodes competing to become part of the CDS in the outer regions of the topology.

In the case of the CDS-Rule-K algorithm, the factor that increases the amount of messages (and energy, consequently) is related to its pruning process in which every node must update nodes two hops away when it is unmarked. This overhead increases with the number of neighbors because more nodes will retransmit the message. Also, when the node degree increases, more nodes get unmarked and will produce this extra overhead.

The linearity of IACDS is a consequence of the bounded number of messages that each node needs to transmit, which remains almost identical and never goes over 4n in ideal conditions. The IACDS algorithm uses four types of messages: hello message, parent recognition message, children recognition message, and sleeping message. Figure 6 illustrates the behavior of the proposed interference-aware CDS topology control algorithm, IACDS, in a graphical manner. In this case, the number of nodes is fixed to 100 and the transmission ranges are varied.

Simulation 2: Changing the node density

The main goal of this simulation is to compare the algorithms when the network density is changed by

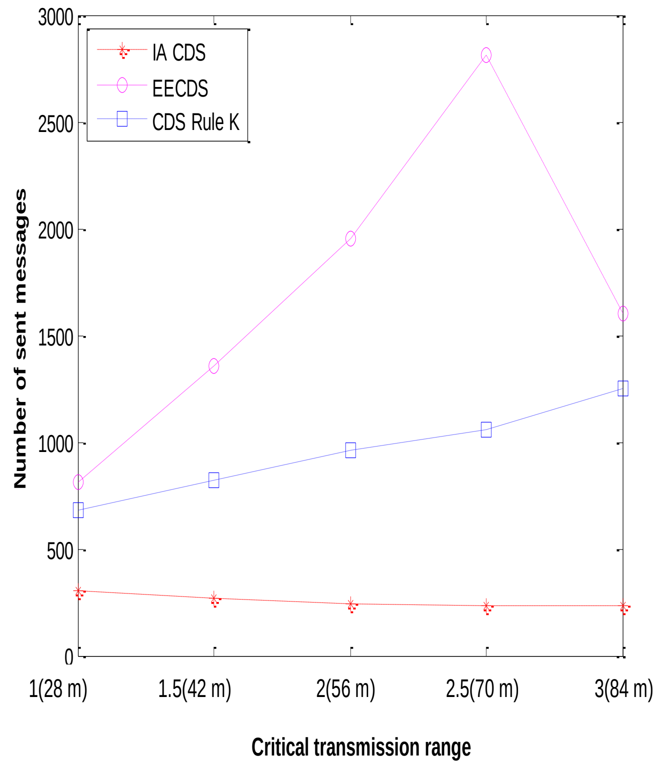

Figure 4. Number of sent messages versus transmission range of the nodes.

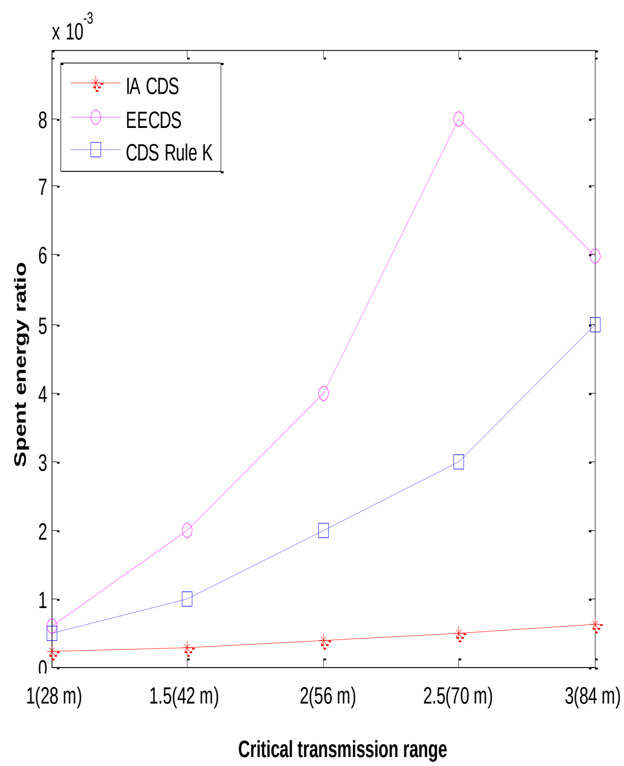

Figure 5. Spent energy ratio versus transmission range of the nodes.

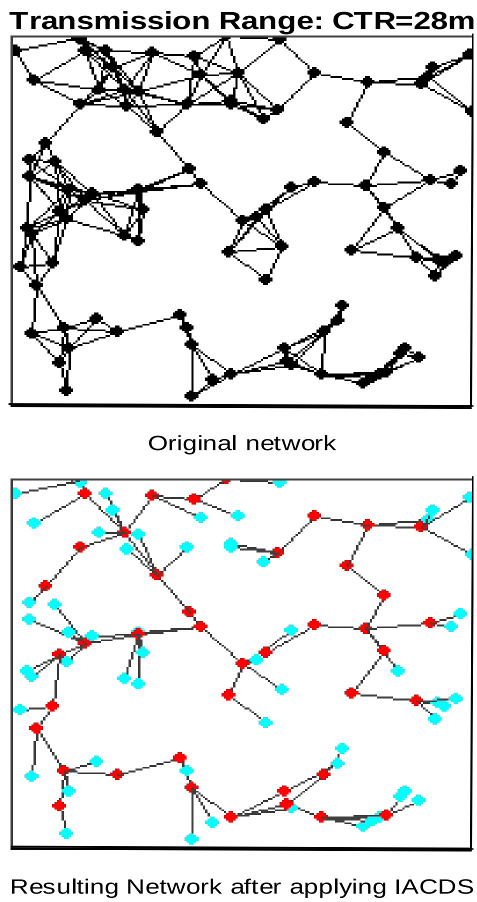

Figure 6. Topologies obtained after applying the proposed algorithm.

varying the number of nodes in the deployment area while keeping a fixed communication range of 63. Communication range of 63 is equivalent in this simulation to 1 × CTR (10).

This simulation is important to show how scalable the algorithms are in dense topologies and how the resource usage depends on the number of nodes. The results shown subsequently are similar to the ones shown in simulation 1.

Figure 7 shows that all algorithms need a similar amount of active nodes, although before 35, CDS-Rule-K shows a small advantage over IACDS, after 35 both EECDS and CDS-Rule-K algorithm go above IACDS. After 60 the CDS-Rule-K algorithm goes up to reach its maximum peak at 80, after 80 it goes down, but still above IACDS algorithm.

Figures 8 and 9 show that in terms of the message complexity and energy efficiency, the trends are similar. The EECDS and the CDS-Rule-K algorithms present a non-linear increase, while the IACDS algorithm shows a low and linearly bounded number of messages and energy consumption. This shows that the proposed algorithm is scalable and is not highly affected by the number of nodes deployed. Figure 10 illustrates the behavior of the proposed interference-aware CDS topology control algorithm, IACDS, in a graphical manner. In this case transmission range is fixed to 63 and the number of nodes is varied.

Simulation 3: Performance using ideal grid topologies

The third simulation considers the ideal grid scenario with two variants of node location distribution: Grid HV and Grid HVD, as shown in Figure 11. This simulation shows the performance of the algorithms in a perfectly homogeneous topology, with ideal condition of density and node degree, which could be considered a predefined scenario. From Figure 11a, it can be seen that the IACDS algorithm shows similar or better results in the number of active nodes metrics, including 58% of the nodes in the Grid HV and 34% in the Grid HVD scenarios, versus 64 and 41% from EECDS, and 61 and

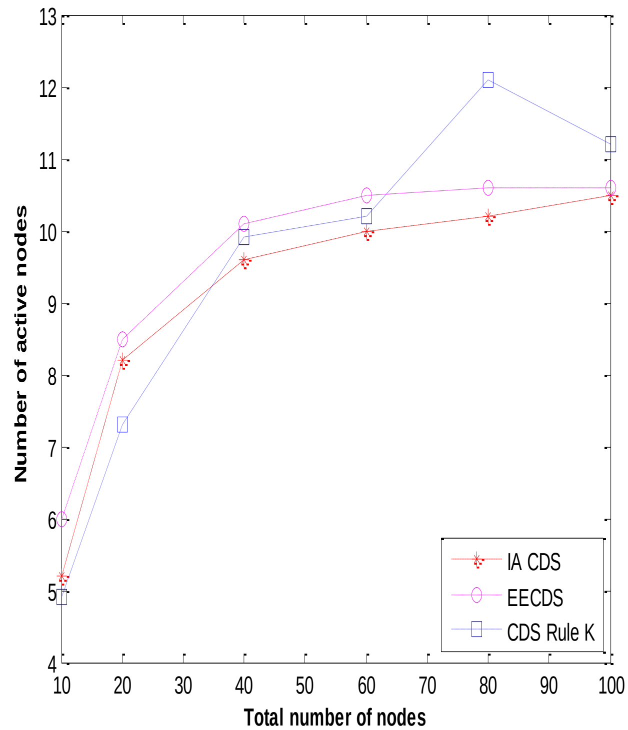

Figure 7. Number of active nodes versus the number of nodes in the area.

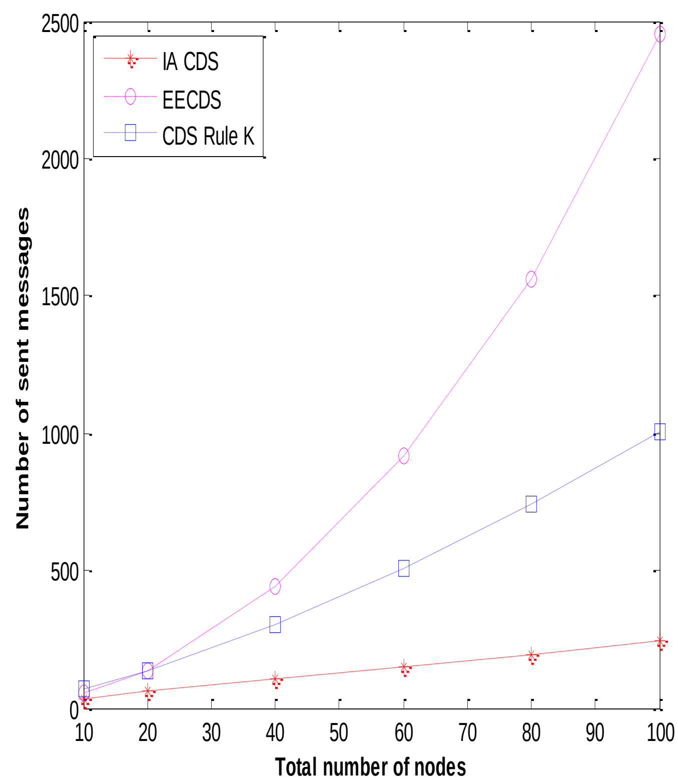

Figure 8. Number of sent messages versus the number of nodes in the area.

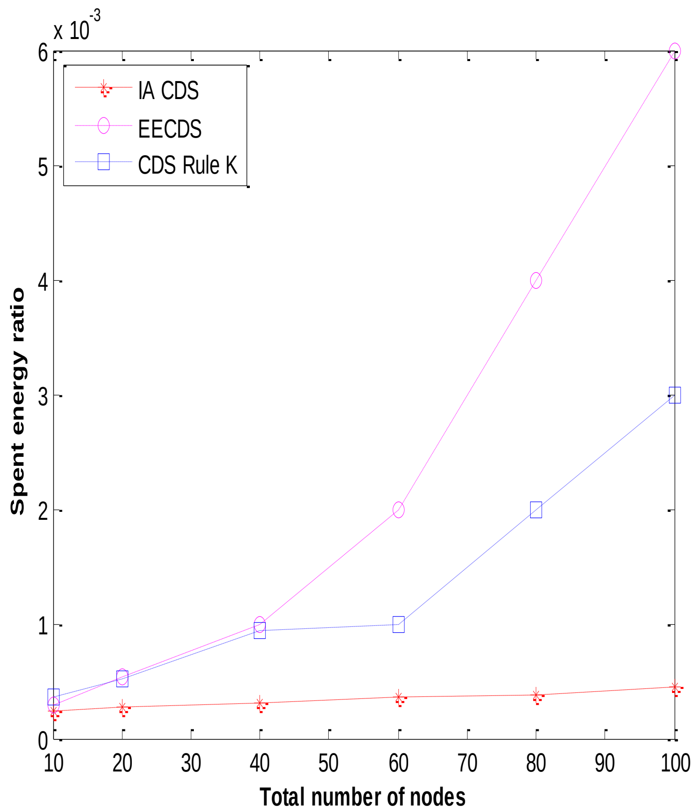

Figure 9. Spent energy ratio versus the number of nodes in the area.

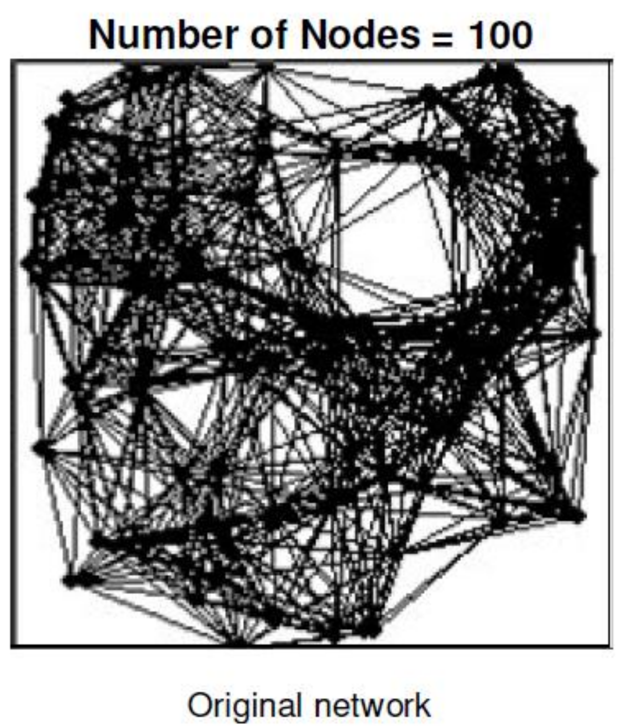

Figure 10. Topologies obtained after applying the proposed algorithm.

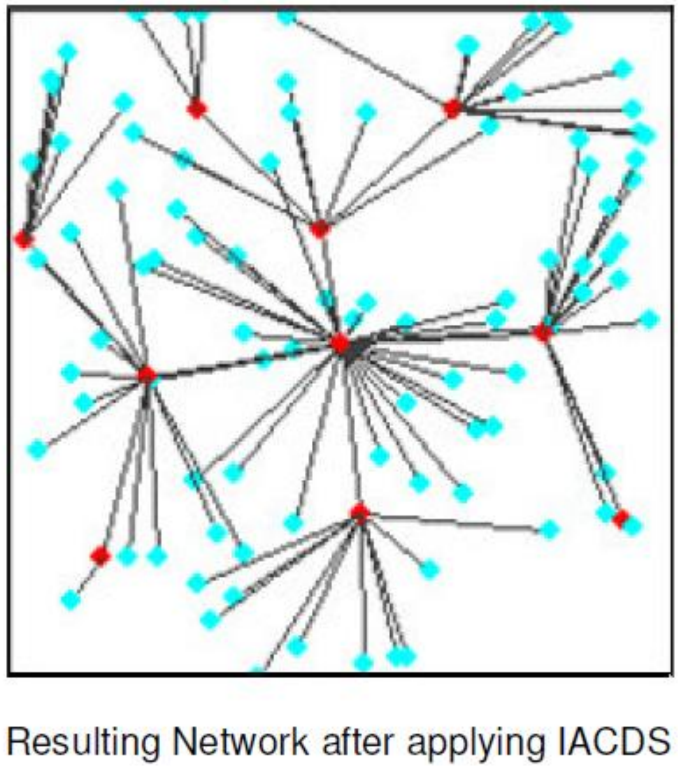

Figure 10. Contd.

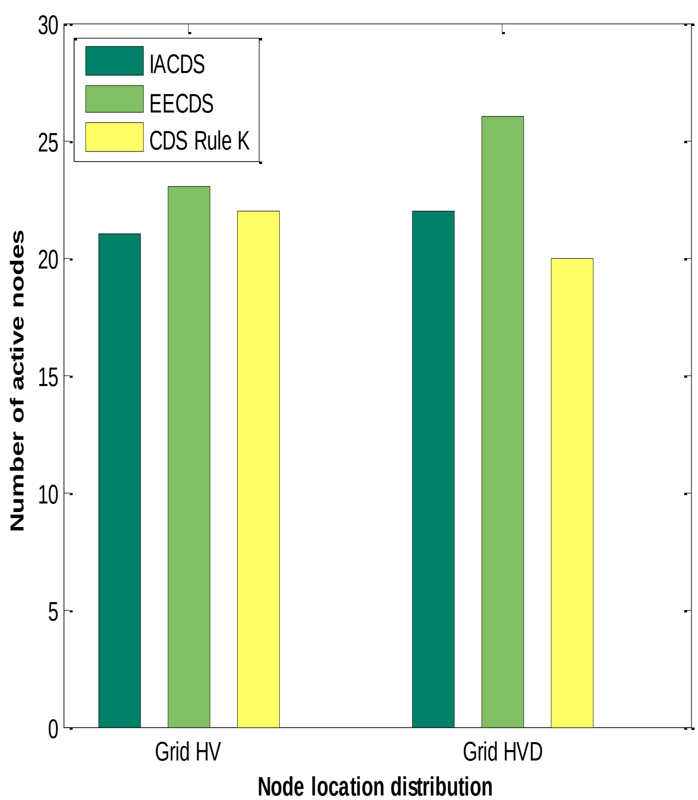

Figure 11a. Number of active nodes.

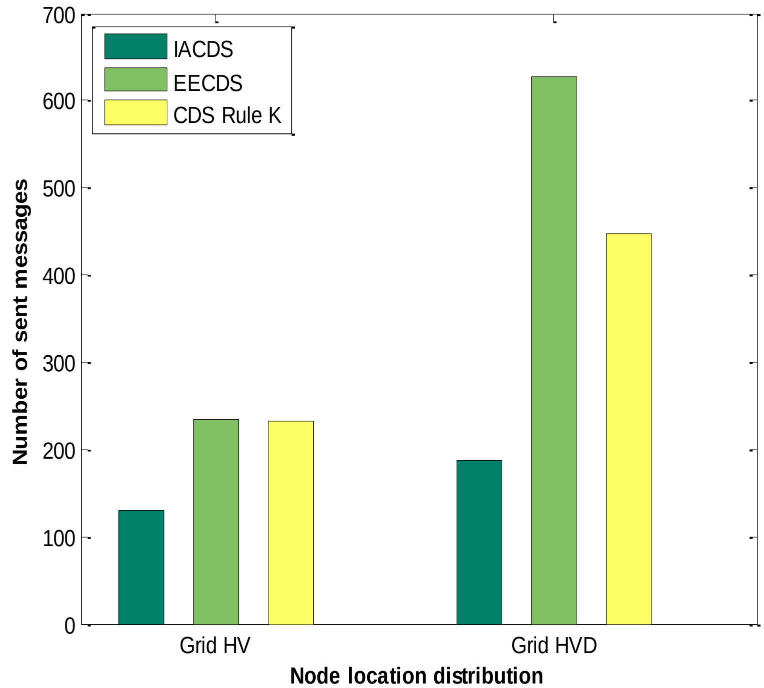

Figure 11b. Number of sent messages.

Table 2. Grid HV and Grid HVD.

Grid H-V	Distribute nodes in the deployment area with a distance of communication radius between nodes, so nodes are adjacent with their vertical and horizontal neighbors.
Grid H-V-D	Distribute nodes in the deployment area with a distance of communication radius × $\sqrt{2}$ between nodes, so nodes are adjacent with their vertical, horizontal and diagonal neighbors.

31% from CDS-Rule-K algorithms. The other two metrics show an increasing trend for EECDS and CDS-Rule-K while IACDS still shows a bounded cost in overhead and energy as seen in Figures 11b and c, respectively. Table 2 summarizes the parameters that can be defined for a homogeneous family of nodes.

Figure 12a shows graphically the behavior of the proposed IACDS algorithm in the case of Grid HV. The number of active nodes is 20 from original 36 nodes. Nodes are distributed in the deployment area with a distance of communication radius between nodes; nodes are distributed close to each other. Results show that the number of active nodes is large with respect to the total number of nodes.

Figure 12b shows graphically the behavior of the proposed IACDS algorithm in the case of Grid HVD. The number of active nodes is 21 from original 64 nodes. Nodes are distributed in the deployment area with a distance of communication radius × $\sqrt{2}$ between nodes; nodes are distributed separate from each other. Results show that the number of active nodes is small with respect to the total number of nodes.

Area of communication coverage

When applying these algorithms, the active nodes determine the communication coverage area. This area is expected to cover as much of the deployment area as possible. Figure 13 shows the average communication area covered by the algorithms using the scenarios from Simulation 2. As it can be seen from this Figure 13, although all algorithms produce an almost similar coverage with the selected active nodes, IACDS is still better; it covers the same or more area but using fewer resources than the others.

CONCLUSION

In this paper, the primary effort has been devoted to

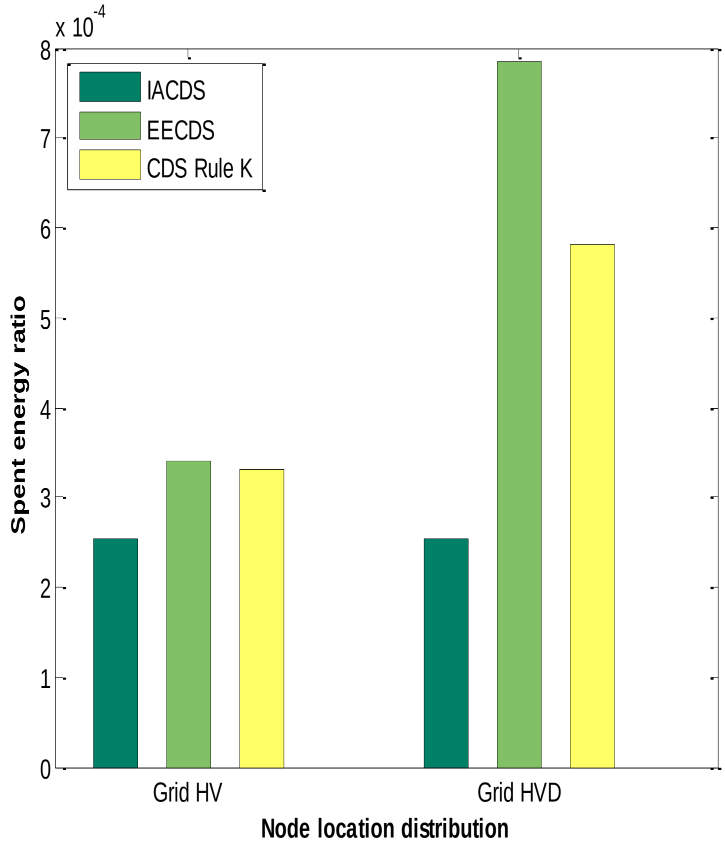

Figure 11c. Spent energy ratio in the CDS creation process.

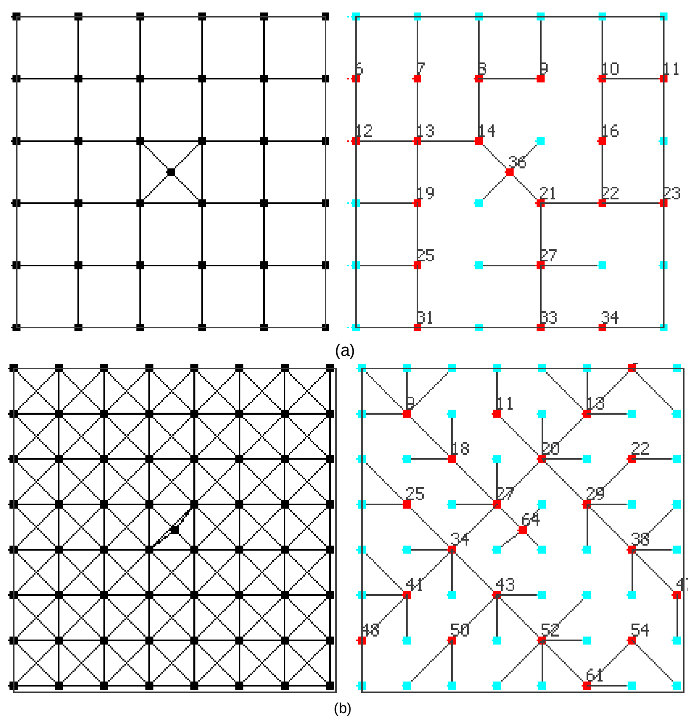

Figure 12. (a) Grid HV node location distribution. (b) Grid HVD node location distribution.

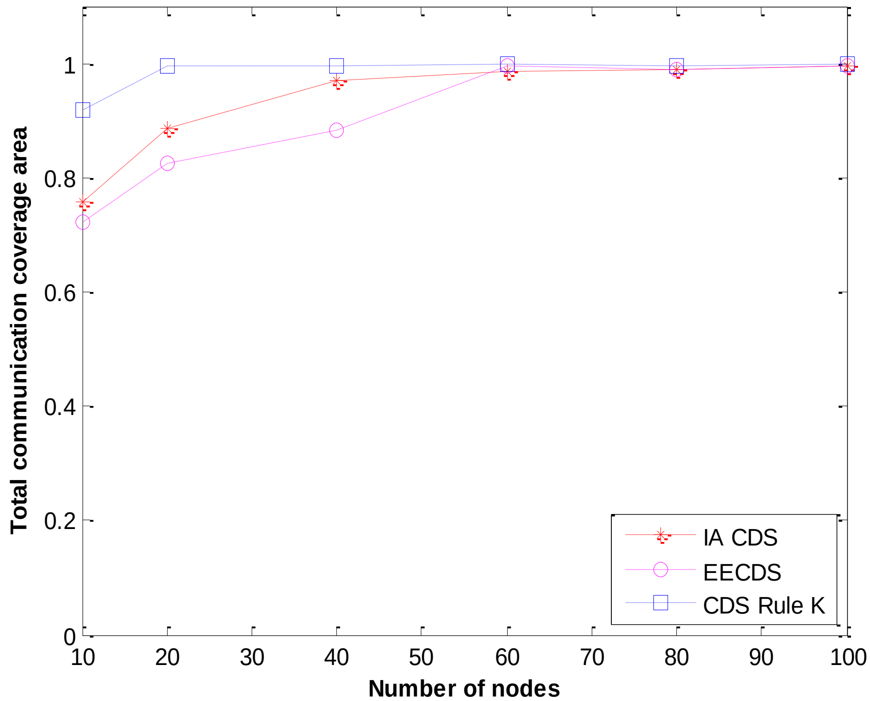

Figure 13. Total communication coverage area.

propose a new topology construction algorithm, namely, IACDS algorithm, a simple, distributed, interference-aware and energy-efficient topology construction mechanism that finds a sub-optimal connected dominating set (CDS) to turn unnecessary nodes off while keeping the network connected and providing complete communication coverage with minimum interference. IACDS algorithm utilizes a weighted distance-energy-interference-based metric that permits the network operator to trade off the lengths of the branches (distance) for the robustness and durability of the CDS (energy and interference). Through extensive simulation experiments, results show the superiority of the IACDS algorithm compared with the existing alternatives, EECDS and CDS-Rule-K algorithms, in terms of number of active nodes needed, message complexity, and energy efficiency.

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