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PAPER

Optimizing Broadcast Utilization for Efficient Disaster Management Using Wireless Ad Hoc Networks and Novel Energy-Saving Algorithms

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ABSTRACT

Globalization, industry, and population growth is considered the main reasons for climate change, so when some natural calamity or disaster occurs in any area, it leads to isolating this area from the rest of the region. Wireless ad hoc networks are important in disaster management to reduce losses and costs as they reduce the response, aiding time to save lives. However, they suffer from limited energy, which controls the lifetime of the sensor. Different methods are applied to save energy and increase battery life, such as sleep-awake schedules which assume similar initial energy for all nodes. Domestic partition in a unit disk graph is the production of the maximum possible number of such disjoint dominants. However, it assumes different initial energy levels for all nodes, which is another problem. In this paper, a new broadcast approach based on minimum set data broadcasting is proposed to minimize the number of broadcasting messages to increase the battery life during disasters and enhance rescue operations. The proposed minimum rebroadcast algorithm (MSRA) method balances coverage and utilization efficiency by dynamically adjusting node selection based on network conditions. The results show that MSRA significantly reduces power consumption and transmission latency, opening the way to find a new solution for disaster management using wireless ad hoc networks.

KEYWORDS

wireless ad hoc, disaster management, minimum connected dominant set (DS), broadcasting efficiency, breadth-first search (BFS), network performance optimization

1 INTRODUCTION

Natural disasters are an unexpected phenomenon that happens in the entire world. Climate change is considered the main reason for natural disasters [1]. such as forest fires, floods, storms, volcanic eruptions, droughts, and others. Dealing with

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a disaster is a very difficult challenge for humans, it requires quick reactions to minimize the cost and save human lives. All efforts focus on the development of a system to predict disaster, plan to prevent it, and respond on time. Disaster management includes all the actions and procedures that are handled during unexpected phenomena that cause billions of people deaths, injuries, and home damages in addition to environmental damages, as it was published by the United Nations Office for Disaster Risk Reduction (UNISDR) report [2].

Wireless technology plays an important role in disaster management. A wireless network is infrastructure that is suitable to be used for emergency services and military applications as it can scale to large scale, be organized easily, and it is free from supported infrastructure [3]. However, wireless sensor networks (WSNs) suffer from limited battery life and limited resources of network nodes, so this causes losses in transmission efficiency in addition to the large mobility changes [4]. Nodes in the wireless network can communicate either directly or forwarding the messages through intermediate nodes. The connected dominant set (DS) is considered the best solution for wireless ad hoc networks to be used as a virtual backbone network [5], so the minimum connected dominant set (MCDS) is used to guarantee the continuity of network operations.

There are many researches done to achieve efficient communication between WSNs that are suitable for disaster recovery operations. These researches have been built on finding a MCDS similar to a virtual backbone network [3]. Most of this research is concentrated on approximating the minimum connected dominant using the virtual backbone network with a minimum size of nodes; try to balance between energy consumption and load. It is clear that all the MCDS algorithms are based on a two-stage method using a maximum independent set and adding a Steiner node to construct a Steiner tree [6]. Broadcasting in WSN is an important factor in supporting many services in WSNs, such as topology discovery, data collection, and code updating. Many algorithms have been proposed to achieve efficient broadcasting by minimizing the number of transmission messages [6, 7]. Minimizing the number of transmissions will save energy. Therefore, a duty-cycled scheme is adopted in WSNs to utilize energy depending on switching between active and passive states of nodes concurrently. All the functional modules are turned off into passive state when one of the nodes are active, as a node may require several transmissions to inform its neighboring nodes, and this is a big challenge to construct the broadcast tree [8].

Efficient disaster management depends on the treatment scenarios necessary to reduce the direct impact of these disasters and reduce response time, which contributes to saving lives. Note that the traditional communications infrastructure is often broken and unavailable due to quarrels, and as a result, it is necessary to use alternative solutions to the traditional communications system, represented using wireless ad hoc networks that do not require infrastructure, as these networks are allocated so quickly to exchange data effectively between rescue teams and disasters' communities. Although they can be provided quickly, they suffer from limited bandwidth, dynamic structural changes, and unreliable communications, which make it difficult to disseminate important information effectively. In this context, our paper addresses the need to propose an innovative algorithm and methodologies that will be used to disseminate information in an optimal way during disasters using the benefits of wireless ad hoc networks. By developing a new algorithm based on the use of minimal rebroadcast procedures, we will enhance the reliability, scalability, and efficiency of information dissemination among disaster management components, thus enhancing response efforts to improve overall disaster resilience.

2 RELATED WORK

Climate change has huge impacts on our world, such as global warming, sea level, and pollution. We may consider climate change as a natural process or a result of human actions. In any case, natural phenomena have increased and become destructive. The movement of sediment, wildfires, storms, and floods will cause problems that affect human life, destroy the economy, and affect development. Therefore, we need to develop a disaster management system to understand natural disasters, then deal with these disasters, predict them, recover after disaster, and save human life. The most important problem that needs to be solved is preserving human lives. Therefore, we need to move within three days after the disaster to save what we can. Any delays would cost us human lives. However, the communications system will be down after the disaster, and the emergency team needs to communicate and share information in order to respond on time [9]. They can use valuable media to communicate, such as sensor networks, robots, satellites, and social networks. However, these methods are not suitable and efficient to be used in natural disaster [10] due to the infrastructure collapse. Therefore, WNSs are the best solution than others.

The development of disaster management using sensor networks has the attention of many researchers, such as flood [11], storm [12], fire [13], sediment transport [14], and more. The sensor is a major element in Internet of Things (IoT) to collect data. The WSN plays a great role in disaster management due to its monitoring and conveying capabilities [15]. However, wireless sensors have limited battery power, and their lifetime is based on the power consumption. Different types of energy-saving methods have been proposed to increase WSN lifetime and coverage [16, 18]. The simplest method is to set the node state to sleep or wake to save power. The WSN is distributing nodes over regions, and it is enough to make one node awake and the rest in sleep state [19]. The forwarded minimum dominating set algorithm is considered the simplest, most compact, and most straightforward rebroadcasting algorithm. It depends on constructing the DS, minimum or not, connected or not to schedule. A node can decide to rebroadcast or not just by looking into the DS. If a node is not in the DS, it will not rebroadcast the packet. It becomes more surprising that if the dominating set was formed in a specific order and a node decided to rebroadcast, it will just look into its location in the vector of DS and then search for its most faraway neighbor, and the difference between the two ranks will be the calculated back off this node [20].

The minimum dominating set algorithm was used to control the node state schedule in a WSN [21]. After that, the concept of domestic partition in unit disk graphs was introduced [22], which is about producing the maximum number of disjoint DSs or based on disjoint weighted DSs [23]. This concept assumes that all nodes have the same initial energy. When considering rechargeable node in WSN, then the initial energy will be different from node to node [22]. A distributed algorithm to construct DSs without direct use of independent sets is proposed [24]. A non-trivial potential function is proposed to increase the connectivity of connected dominant sets (CDS) [25]. The algorithm decomposes two connected graphs into three connected components, called Tutt's decomposition.

In WSNs, models such as disk graphs (DGs), depth-first searches (DFS) and unit disk graphs (UDGs) are used to study the performance of WSNs. An improvement was made on the search techniques using the variable depth search method [26]. The algorithm can traverse large spaces in a minimum time.

In radio networks, some researchers try to study the problem of minimum-latency broadcast scheduling. The reachability of all nodes is based on neighborhood information [27]. The backbone-based technique is treated as part of a topology-based approach [28]. Where the main goal of the communication backbone approach is to find a subset of nodes that will guarantee connectivity and communication coverage throughout the deployment area while allowing every other node in the network to reach at least one node on this backbone in a direct way.

Connected dominant set is considered a better choice for WSNs as the virtual backbone network. It guarantees the operation of the network by constructing the MCDS [29]. A new degree based greedy approximation is proposed to connect the pseudo-dominating set [30] by using two hops information in order to reduce the CDS size. DFS is one of the most significant graph search algorithms, as it can strongly find the connected components and test their planarity. DFS has much lower memory requirements than breadth-first search (BFS), because it's not necessary to store all of the child pointers at each level [24].

It is clear from recent literature that there are several key algorithms and methodologies that provide unique strengths and address specific challenges in using WSNs in disaster management.

The Bat algorithm is used to activate sensor nodes [31] to provide a new approach that uses the Bat algorithm to efficiently activate sensor nodes, ensuring target coverage connectivity in WSNs. However, their performance may be limited by network density and needs to be further investigated using tuning mechanisms to enhance performance in diverse environments. Predictive modeling techniques for IoT-based data transmission [32] are used to enhance energy efficiency in WSNs by adapting predictive modeling techniques to explore the applicability of predictive models in different WSN scenarios and evaluate quality of service (QoS) and energy efficiency. However, there is a need to explore the applicability of predictive models in different WSN scenarios and evaluate the energy efficiency and QoS of the transmitted data.

Additionally, the predefined path constrained mobility for mobile sinks [33] addresses energy consumption challenges in mobile sink scenarios by utilizing predefined paths for data collection. However, scalability concerns and the exploration of adaptive path planning techniques based on real-time network conditions remain areas for improvement. Furthermore, the hierarchical clustered fault-tolerant routing (HCDSR) [34] introduces a hierarchical clustered routing technique tailored for IoT-based smart societies, focusing on fault tolerance in routing for enhanced reliability. Similarly, the energy-aware QoS MAC protocol based on prioritized-data and multi-hop routing [35] proposes a MAC protocol designed for energy efficiency and QoS in WSNs, prioritizing data transmission and utilizing multi-hop routing for improved network performance. Despite their strengths, both approaches could benefit from investigations into their performance under varying network conditions and the optimization of parameters to further enhance energy efficiency and QoS metrics. In addition, pre-defined path-constrained mobility for mobile sinks [33] addresses the energy consumption challenges in mobile sink scenarios by using pre-defined paths for data collection. With a focus on network expansion to explore adaptive path planning techniques based on real-time network conditions. Furthermore, HCDSR [34] is used.

Using a hierarchical clustered routing technology specifically designed for IoT-based smart communities, which is associated with fault tolerance in routing. Similarly, an energy aware QoS MAC protocol based on prioritized data and multi-hop routing [35] uses a MAC protocol designed for energy efficiency and QoS in WSNs, which focuses on data prioritization that uses multi-hop routing to develop performance. Despite their strengths, both approaches can benefit from investigations into their performance under different network conditions using energy efficiency and QoS metrics. Researchers combine multiple localization strategies to improve localization accuracy, combining optimization (ABO, DSA, EHO, KNN) and neural computing techniques (BP, MTLSTM, BILSTM, Autoencoder) in three phases: data collection, model building, and implementation [36]. This makes it valuable for numerous applications such as environmental monitoring, healthcare, smart cities, and disaster management. The main goal of all this research is to save lives. There is a good survey that explores modern technologies such as data communication networks (DCNs) and the IoT, analyzes traditional and modern signal processing techniques, and the role of remote sensing, robotics, drones, and social media [37, 38, 39]. Also summarizes optimization techniques and important functions of artificial intelligence (AI) in seismology, guiding stakeholders to prevent disaster and save human life.

Table 1. A summary for recent algorithms in wireless sensor networks for disaster management

Algorithm	Key Strengths	Limitations	Areas for Improvement
Bat Algorithm for Sensor Node Activation [31]	– Utilizes bat algorithm for efficient sensor node activation – Ensures connected target coverage in WSNs	– May require fine-tuning of algorithm parameters for different network scenarios – Performance impacted by network density and target distribution	– Investigate adaptive parameter tuning mechanisms for improved performance in diverse environments – Evaluate scalability and robustness of the algorithm in large-scale WSN deployments
Predictive Model Techniques for IoT-Based Data Transmission [32]	– Utilizes predictive model techniques to enhance energy efficiency in WSNs – Focuses on IoT-based data transmission	– Specific limitations not provided	– Investigate the applicability of predictive models in diverse WSN scenarios – Evaluate the trade-off between energy efficiency and data transmission latency
Predefined Path Constrained Mobility for Mobile Sinks [33]	– Utilizes predefined paths for mobile sinks in WSNs to optimize energy-efficient data collection – Addresses energy consumption challenges in mobile sink scenarios	– Specific limitations not provided	– Investigate the scalability of the proposed method with larger WSN deployments – Explore adaptive path planning techniques based on real-time network conditions
HCDSR (Hierarchical Clustered Fault-Tolerant Routing) [34]	– Introduces a hierarchical clustered routing technique tailored for IoT-based smart societies – Addresses fault tolerance in routing for enhanced reliability	– Specific limitations not provided	– Investigate the performance of HCDSR in large-scale IoT deployments – Explore adaptive fault-tolerance mechanisms to handle dynamic network conditions

3 METHODS

In this paper, we propose a novel minimum set rebroadcasting algorithm (MSRA). The proposed algorithm starts from A start node S and then goes from the second level because level one primary node has been determined. It includes two phases, starting with the initialization phase, and then proceeding to the parent node phase as shown in Figure 1.

- Initialization phase:
  1. First initializing the dominating set vector P to the root node s and a temporary storage Temp to the set of all networks (graph) nodes.
  2. Then constructing the breadth first search tree (TBFS) and its depth (l), which is the number of hops from the root to the farthest node.
  3. After that, initializing each level of the tree with its nodes and the set of neighbor nodes for each node ($Ni(w)$).
- Parent node phase: the main core of the algorithm starts in this phase.
  1. It starts from level two and chooses the parent for each node (w) in the graph. This step is a challenge in the construction of the broadcast vector.

2. Check if any node in the dominating set vector (*P*) is dominating this node; otherwise, treat it as a secondary node:
   - If there are common nodes between *P* and *W*'s neighbors, the parent node may be in the same or previous level.
   - If the node *w* is a leaf node, treat it as a secondary node.
   - If node *w* has no neighbors in the next level, add the node itself and its parent in the previous level with maximum degree to vector *P*.
3. Based on the conditions in equations 1 and 2, determine if node *w* is a leaf node or secondary node covered by a node in *P*.
   a) If there are common nodes between *P* and *W's* neighbors, the parent node may be in the same level or the previous level.

$$\text{if } (P \cap Ni(w) = \varnothing) \quad (1)$$

   b) If the node *w* is a leaf node, then it is treated as a secondary node.

$$\text{AND } [(Li + 1 \cap Ni(w)) \neq \varnothing] \quad (2)$$

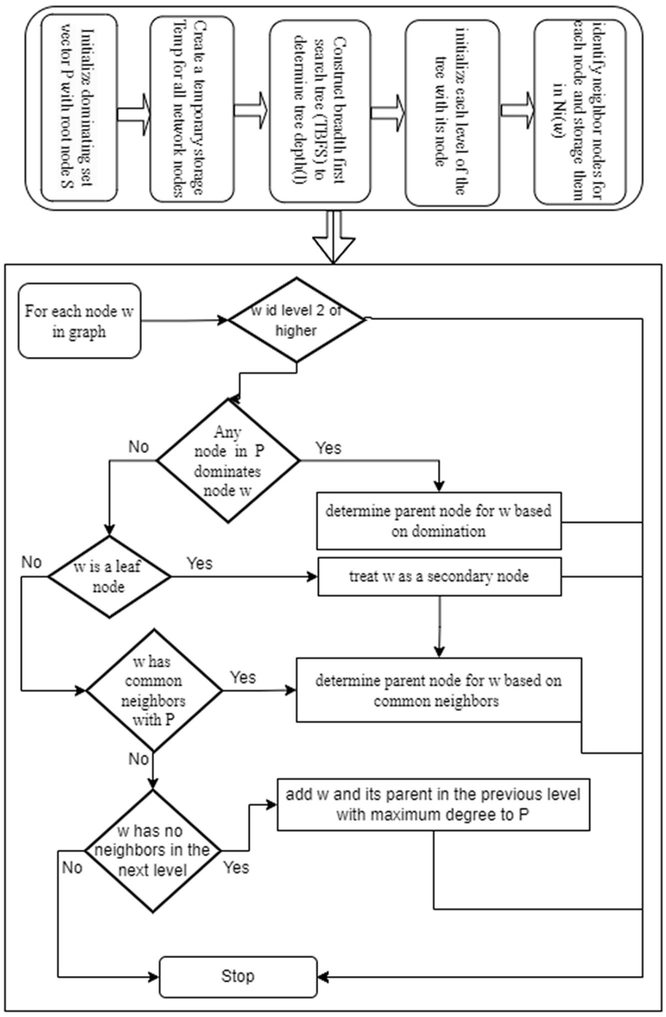

Fig. 1. Minimum set rebroadcasting algorithm process details

   c) If node *w* has no neighbors in the next level, then the node itself and its parent in the previous level with maximum degree (to have one parent only) will be added vector *P*.

d) If conditions in equations 1 and 2 are not met, it means that one of them or both are not met. This means that node *w* may be a leaf node or secondary node, can be covered by a node in *P*.

$$\text{if } (P \cap Ni(w) = \varnothing) \text{ AND } [(Li + 1 \cap Ni(w)) = \varnothing] \tag{3}$$

Figure 2 illustrates an example of FMCDS when the parent of a leaf is not in *P*.

- **Broadcast scheduling:** The message arrives collision-free to all nodes with a latency of 6t, equal to the cardinality of the FMCDS, with no redundant transmissions.
- **Algorithm analysis:** MSRA balances coverage area and utilization efficiently compared to traditional methods, is robust to node failure, and adaptable to architecture changes, making it promising for disaster management using ad hoc networks.

In case of false: node w is a secondary node and can be covered by a node in *P*. But if the result was true, then node *w* is a leaf node and not covered by any node in *P*, so only the parent of *w* will be added to *P*. Table 2 below simplifies the conditions.

Table 2. Truth table for conditions

$P \cap Ni(w)$	$Li + 1 \cap Ni(w)$	Meaning	Decision
$= \varnothing$	$= \varnothing$	Not covered leaf	Add parent only
$= \varnothing$	$\neq \varnothing$	Not covered not leaf	Add parent then add *w*
$\neq \varnothing$	$= \varnothing$	Covered leaf	No addition
$\neq \varnothing$	$\neq \varnothing$	Covered not leaf	No addition

Figure 2 below shows an example of FMCDS when the parent of a leaf is not in *P*. Assume that node 7 was reached in constructing the FMCDS, *P* will be {*s*, 1, 3, 2, 5}. Applying Equation (3).

$P \cap Ni(7) = \{s, 1, 3, 2, 5\} \cap \{4, 6, 7, 8\} = \varnothing$ AND $((Li + 1 \cap Ni(w)) \neq \varnothing)$

Therefore, Node 7 is a leaf node and not dominated by any node in *P*, so the only node that will be added to *P* is the parent of node 7 as follows:

parent (7) ← any node *v* in *Li*–1 that dominates *w* and has max. $Ni(v) = \{4\}$
P ← *P* □ {parent (*w*)} = {s, 1, 3, 2, 5, 4}
Now *P* = {*s*, 1, 3, 2, 5, 4}, and it will be the same after fetching node 8.

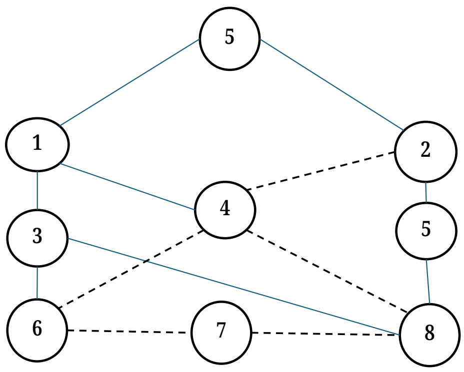

Fig. 2. Example of FMCDS

The new change adds a new primary node 3 instead of node 4, while node 4 will be the last node in the dominating set. When it receives the message, it will calculate its backoff time as follows, noting that node's 7 rank is 5 and its parent rank is 3, which is the rank of node 1:

For node 4: Timer value T4 = t * (5-3-1) = t

Which means that node 4 will wait t time after it receives the message, Table 3 illustrates the broadcast schedule for all nodes after this new change.

Table 3. Broadcast scheduling for the example

	S	1	2	3	4	5	6	7	8
0	Tx	Rx	Rx	–	–	–	–	–	–
t	Rx	Tx	Waiting	Rx	Rx	–	–	–	–
2t	–	Rx	Waiting	Tx	–	–	Rx	–	–
3t	Rx	–	Tx	–	Rx	Rx	–	–	–
4t	–	–	Rx	–	waiting	Tx	–	–	Rx
5t	–	Rx	Rx	–	Tx	–	Rx	Rx	Rx

So, the message arrived collision free to all nodes and with a latency of 6t, which is equal to the cardinality of the FMCDS. It is noted that there are no redundant transmissions.

The minimum rebroadcast algorithm (MSRA) introduces a new two-stage approach that facilitates data propagation in dynamic networks. By adapting the original node selection to the exact configuration, as described in the Results section, MSRA will balance the coverage area and its utilization in an efficient manner compared to traditional methods. MSRA will adjust and create node selection based on network conditions to optimize coverage area, latency, and battery life. MSRA is robust to node failure and adaptable to architecture changes, making it a promising solution for disaster management using ad hoc networks. So MSRA will overcome communication challenges in subterranean environments.

4 RESULTS AND ANALYSIS

4.1 Low density network

If the network consists of n nodes making a string topology, then the size of the minimum dominating set (MDS) is n–1. the worst case for MCDS is when a network consists of cascaded nodes, with a complexity of O(n–1).

4.2 High density network

Conversely, if the node chosen in a high-density network is dominated by all other nodes, then the minimum dominating set is that point, and in general, if the network consists of n nodes making a mesh graph, then the minimum dominating set is the first node chosen by the algorithm. According to lemma 3, the best case for MCDS size is when a network consists of mesh network nodes and has Big O complexity O (1).

4.3 Effect of transmission range R

Increasing the transmission range R via power augmentation or utilizing the use of high gain antennas will assist in enhancing the coverage area of any node, potentially encompassing more nodes within a node's communication radius. This means that new nodes may be covered, and it will increase the degree of a node, and minimize the number of levels in the BFS tree, thereby inversely affecting the minimum dominating set.

4.4 Broadcast saving

To check the amount of broadcast saving and compare it to the tree-based approach, the random distribution will be used, the area of the network will be fixed to 300 × 300 meters, the transmission range will be fixed to 100 meters, noting that these two parameters were not clear in [34], and the last parameter will be the number of nodes that are from 10 nodes up to 100 nodes. Also, it should be mentioned that as CDSSIM randomly distributes the nodes inside the network, the simulations were run many times to get the case where all nodes are covered, then calculate the average readings.

Figure 3 shows the number of levels of the BFS tree, and Figure 4, shows the average degree of neighbors for the nodes. These figures show that increasing the number of nodes has a minimum effect on the maximum number of levels of the BFS tree, it increased the average degree of nodes dramatically.

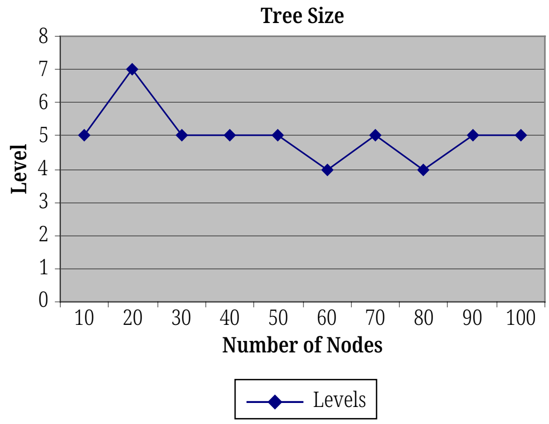

Fig. 3. The number of levels of the BFS tree

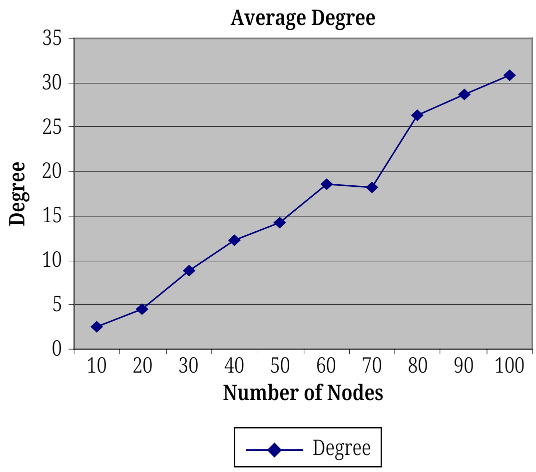

Fig. 4. The average degree of neighbors for the nodes

If we look at the size of the dominating set, i.e., the nodes responsible for retransmission for both algorithms, Figure 5. shows the huge difference between the two schemes. Figure 6 shows the effect of the size of the dominating set on broadcast saving. We can see the big saving the FMCDS provide over the tree-based approach, where FMCDS saved on average 78%, while tree based had on average 30% saving.

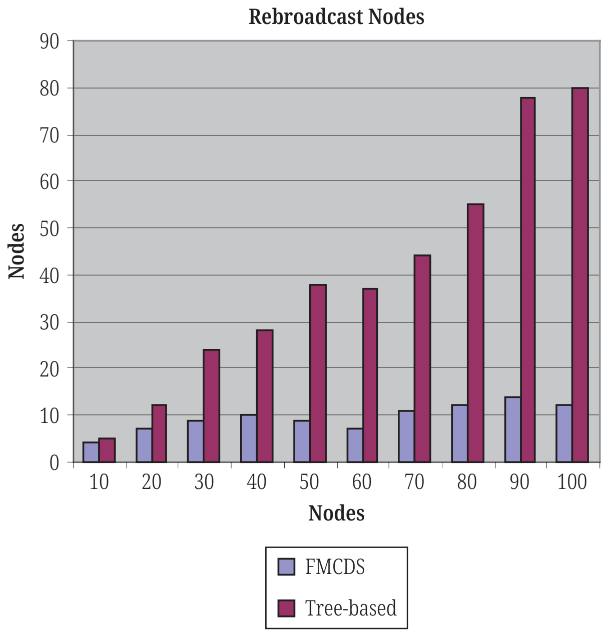

Fig. 5. Dominating set size FMCDS vs. tree-based

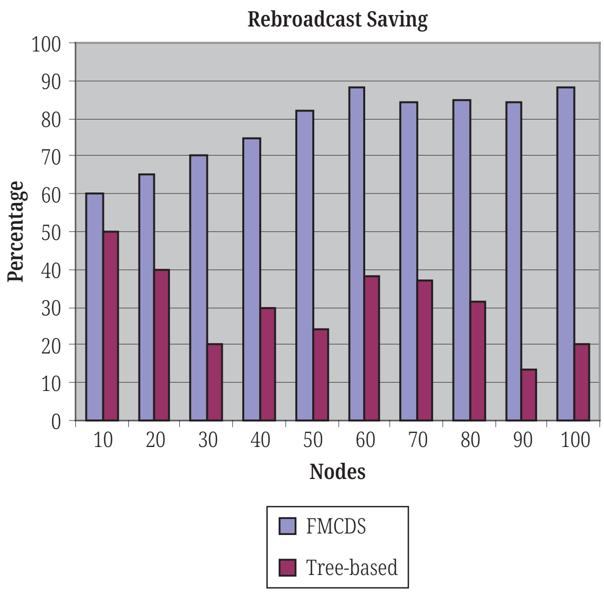

Fig. 6. Broadcast saving FMCDS vs. tree-based

A smart broadcast algorithm to deal with the broadcasting problems in static wireless ad hoc networks was done. The solution is based on constructing a backbone for the transmitting nodes by constructing what is called the MCDS. Arrange it in a special format after constructing the breadth first search tree (BFS) and propose a new way to schedule the broadcasting by sending the MDS itself with the broadcasted message, and each node will decide to cancel broadcasting or to broadcast, then schedule its retransmission by finding its calculated backoff according to its position in the MCDS. Both algorithms were analyzed and proved that the proposed algorithms can give the minimum dominating set in most of the cases with the minimum number of steps and that scheduling the rebroadcasting will prevent the collision effect and will minimize the total latency. Also proved that obtaining both MDS and scheduling rebroadcasting are NP-complete problems.

Then the effect of different network parameters on the size of the dominating set was studied, where it was proved by simulation that the number of nodes has a small effect on the size of the dominating set and that other parameters like degree, transmission range, area, and tree levels have more effect. An approximation for the size of the MDS in special cases was proposed and proved by simulation; this approximation depends on the average degree and the depth of the BFS tree.

The proposed simulator CDSSIM was introduced and used to prove the effectiveness of the FMCDS algorithm in broadcast saving over the tree-based approach.

In this study, valuable results were obtained and can be applied to different scenarios in real disaster management, as the proposed algorithm benefited from the formation of the minimum connected control group (MCDS) and smart broadcast scheduling, enhanced communication reliability, reduced access time, and improved network efficiency. By creating an efficient backbone for MCDS, the algorithm ensures reliable delivery of messages across various scenarios, including node failure and network outages. It also reduces collisions and latency, which is considered a key factor in dealing with the effects of disasters due to the sensitivity of response time. However, several challenges arise, such as computational complexity, scalability, and network dependency. We will focus on optimization as future research to deal with dynamic adaptation and integration with emerging technologies. Verifying the effectiveness of the algorithm in the real world in disaster scenarios is essential to demonstrate the success of its deployment and adoption, ultimately contributing to more robust and efficient disaster management.

5 CONCLUSION AND FUTURE WORK

This study emphasizes the need for leveraging the transmission backbone in wireless ad hoc networks to be implemented in disaster management, with special emphasis on building a MCDS using a BFS algorithm. The use of MCDS based on BFS will provide optimal broadcast technology for the communication process. Moreover, efficient rebroadcast scheduling will enhance network efficiency. It is revealed that both MCDS construction and rebroadcast scheduling are NP-complete problems. To address these challenges, an intelligent and compact broadcast algorithm is proposed as a solution. This innovative solution builds the MCDS and arranges it in a specialized format. Unlike traditional approaches, where MCDS construction and rebroadcast scheduling rely on centralized tasks executed using the message root, the proposed solution relies on distributing responsibility among network nodes. This will enable each node to independently decide whether to broadcast or cancel the transmission, thus contributing to mitigating and reducing the probability of collision, leading to minimum overall latency. Moreover, the proposed study reveals that the size of the dominant group is only slightly affected by the number of nodes. Instead, there are factors that have a greater influence, such as node degree, transmission range, network area, and tree levels. The proposed study presented an approximate method for estimating the size of MDS in specific scenarios, demonstrating its possibility of relying on both the average node degree and the depth of the BFS tree. There are several future research areas that present themselves as optimization methods for the proposed broadcast algorithm in scenarios with different conditions, such as dynamic network usage or variable traffic loads. In addition, the study of distributed methods, such as routing and resource allocation, holds promising solutions to enhance the overall performance of the network.

Moreover, extending the proposed approximation method for MCDS scaling to broader scenarios in networks and topologies can contribute to process improvement. Through rigorous verification and optimization based on extensive simulation studies or real-world experiments. In conclusion, the results and methodologies presented in this study represent good solutions for further progress in improving broadcast efficiency and network performance in wireless ad hoc networks, which contributes to increasing the possibility of benefiting from this type of network in improving natural disaster management.

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