Impact of Network Density on Bandwidth Resource Management in WSN

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Abstract. We describe a self-organizing, clustering protocol for bandwidth resource management in Wireless Sensor Networks. The proposed protocol allows the sensor nodes to communicate by a time-slotted, scheduled MAC algorithm. When the nodes are densely deployed, i.e., the connectivity is very high, the MAC algorithm may not provide access for all of the nodes due to the limited number of time-slots, consequently the network capacity degrades. To overcome this drawback, we extend the time-slotted MAC algorithm by clustering the nodes into different frequency domains while they can use the same time domain. The idea is basically to multiplex the time domain with the frequency domain. As a result, the number of nodes that are granted access to the wireless medium is increased by the number of frequency channels available. By using simulations, we evaluate the performance of the protocol. The results reveal that frequency multiplexing has the effect of increasing the capacity up to 100%.

1 Introduction

Wireless sensor networks (WSN) [1] are defined as a sub-class of wireless ad hoc networks [2] that enable monitoring, inspection and analysis of unknown, untested environments. A WSN typically comprises a large number of tiny embedded sensor devices. The sensor devices are designed to collect sensorial data and to transmit the readings by wireless communication.

Large-scale and dense deployment have advantages (spatial coverage extension, higher resolution of information, fault tolerance and robustness) over the traditional sensing methods. The ad hoc nature make WSN attractive for a broad range of new applications.

The number of sensor nodes deployed in studying a phenomenon may be on the order of hundreds or thousands [1]. Depending on the application, the number may reach an extreme value of millions. The schemes proposed for WSN must be able to work with this number of nodes. The scope of this paper is how to manage the communication among sensor devices in a large scale WSN. Due to the disadvantages of wireless communication, such as consuming a lot of energy, being prone to failures and limited range, the MAC layer which controls the wireless medium access, has large impact to regulate the wireless communication [3]. Considering this, we use the LMAC protocol [4], which is a light-weight MAC protocol proposed for WSN. It is based on scheduled access. Each node gets a turn (time slot) to transmit its data. The time slots are assigned in a self-configuring and localized way, so that the protocol does not depend on a central manager. Time slots can be spatially reused, just like frequency reuse in GSM [5], due to the multihop nature. The LMAC algorithm is proven to be performing well [3] against some other MAC algorithms like SMAC [6], TMAC [7], LPL [8] and IEEE 802.11. Moreover Law et al. [9], investigates the susceptibility of LMAC in link layer jamming attacks from the security point of view. The details of the LMAC algorithm will be given in Section 3.

Besides the advantages, LMAC's operation is dependent on the number of time slots, so to the density and connectivity of the network. When there are no more free slots (i.e. the local connectivity is higher than expected), the node cannot access the wireless medium and remains in the searching phase for a slot. The number of time slots necessary in a network grows rapidly with increasing connectivity. Therefore, we need a mechanism that reduces the maximal connectivity in the network. The simplest method would be to reduce the transmission ranges of sensor devices. However, this approach may cause the disconnection of nodes that are located far away from the others [10]. If a node does not have communication links, it cannot exchange information and becomes useless.

We propose to multiplex the time slots with the frequency domain. With ethod, the sensor nodes will form clusters by communicating in different frequency domains. The critical resource *bandwidth* will be re-used by that number of frequencies available in the same time domain. The connectivity in the network will be reduced by the number of frequencies. This approach is similar to the idea used in cellular networks. In cellular networks, different frequencies are assigned to each cluster (frequency reuse is also available). Within the cluster, clients use different time slots whereas they are sharing the same time slot with another client in another cell. However, WSN lack base stations and our study does not rely on a central manager which makes the fixed channel assignments. Instead, we propose to use self-organizing distributed algorithms.

The rest of the paper is organized as follows; in Section 2, related work is summarized. Section 3 explains the LMAC algorithm. Section 4 presents the frequency-multiplexed LMAC algorithm. Section 5 reveals experimental results of simulation. Section 6 discusses some concluding remarks for future work.

2 Related Work

We can relate the work studied in this paper to two well-known subjects in the field of wireless networks. First is the channel assignment problem and the next is the capacity issues of wireless networks. Our work is the combination of these two issues and studied in the WSN domain, sub-field of wireless networks.

The channel assignment problem in wireless networks has been deeply studied in cellular networks and ad hoc networks. In GSM, different frequency domains are used for different cells per base station while within a cell clients are sharing the time domain to access the wireless medium. Our work is an extension of this idea. However, we are using self-organizing distributed algorithms instead of central and fixed assignments. Naghshineh et al. [11], present a comprehensive survey for the problem in telecommunications systems. Sengoku et al. [12], tackle the problem from the graph theoretic point of view. Youngs et al. [13], emphasize the work on frequency assignment problem. Leung et al. [14], study the frequency assignment for IEEE 802.11 wireless networks. They state that, due to the coupling between the physical and MAC layers, conventional frequency allocation methods for typical cellular networks cannot be applied directly to the 802.11 networks.

In recent past years, there has been a significant effort [15], [16], [17] on increasing the performance of wireless ad hoc networks since Gupta and Kumar [18] prove that the capacity of a fixed wireless network decreases as the number of nodes increases. Gupta and Kumar derive the capacity of ad hoc networks which is defined as node capacity to be expected in the network. Much more related to WSN Dewasurendra [19] et al. present a brief survey of recent research on scalability of protocols for wireless ad-hoc networks and discuss the scalability issues in WSN.

In the WSN domain, Waharte et al. [20], studies the performance of distributed frequency assignment algorithms for WSN. The motivation is to use different frequencies in classical clustering approaches for WSN to avoid intercluster interference. They model the frequency allocation problem as a distributed constraint satisfaction problem [21] and compare three solutions: Asynchronous Backtracking, Asynchronous Weak Commitment [22] and Distributed Breakout Algorithm [23]. The distributed algorithms we propose are also localized, collaborative algorithms but not from the viewpoint of the distributed constraint satisfaction problems.

3 The LMAC Protocol

Main properties of the LMAC protocol [4] for multi-hop WSNs are that:

- Self-configuration.
- Robustness against high peak loads
- Energy-efficiency, ensuring a long-lived network.

The specialty of the LMAC protocol is that it allows cross-layer optimizations by providing network information to higher layers in the communication stack.

The LMAC protocol enables the communicating entities to access the wireless medium on a time-scheduled basis. This method has a natural advantage of collision free medium access. Because collisions are a big overhead in energy wastes, which is a an important issue in WSN. Since the sensor nodes are assumed to be useless when they run out of battery. A node that intends to do transmission takes control of a time slot. When a node is the intended receiver it is notified. Moreover, when a node is not needed for communication it can switch to standby mode to conserve energy.

Like other time-scheduled MAC algorithms, LMAC also considers the time divided into frames which are further divided into time slots. When a node has some data to transmit it waits until its time slot. Other nodes should always listen at the beginning of time slots (control message interval) to query whether they are the intended receivers. The execution model of LMAC is represented in Figure 1.

```
While (battery_level != 0)
do
   if(current_slot == controlled_slot)
      Transmit
   else
      Receive
      Update synchronization
   Update current_slot
done
```

Fig. 1. LMAC protocol execution model

The time slot selection mechanism in the LMAC protocol is fully distributed and thus needs no base stations or central managers that can decide and allocate the time slots for the nodes. The multi-hop nature of the WSN allows the time slots to be reused. The number of time slots that can be used per frame closely depends on the maximal connectivity of the network.

For spatial reuse of time slots, the nodes use an algorithm based on local information only. Active nodes transmit a small table in the message that contains those time slots the node considers to be occupied by itself and its 1-hop neighbor nodes. This information is efficiently encoded by a number of bits equal to the number of time slots in a frame. Nodes can start controlling a time slot when the slot is considered free by all its neighbors. This method ensures that a time slot is only reused after at least 2-hops.

The distributed algorithm for time slot selection is represented in Figure 2.

All the nodes maintain vectors of length equal to the number of timeslots for storing the occupied slots within the 2-hop neighborhood and local occupied slots to identify the time slots controlled by the 1-hop neighbors.

When there are no more free slots (i.e. the local connectivity is higher than expected), the node remains in initialization state, periodically monitoring frames to find an empty time slot. Reserving a time slot for each node in the network may be a possible solution. However, this would simply make too long waiting periods, before nodes get the opportunity to transmit and force the nodes to communicate in a predefined pattern of communication. For this reason, the frame interval should be kept as short as possible and reused as much as possi-

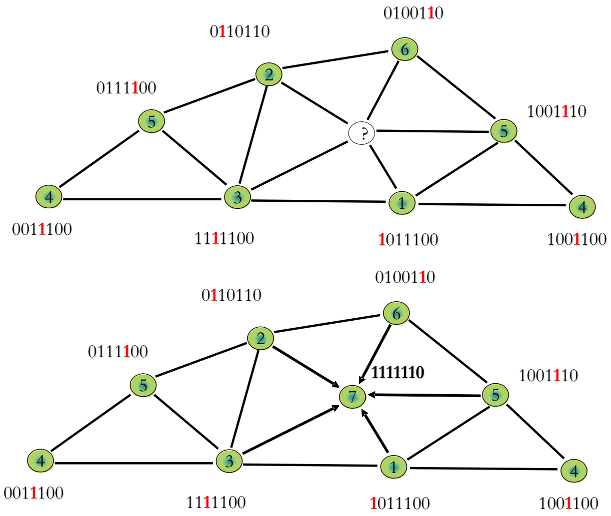

Fig. 2. LMAC Protocol: The node labeled ? does not have a timeslot.

ble. At the moment in the LMAC design, 32 time slots in a frame with a total length of 1 second are considered.

4 Frequency Multiplexed LMAC

As an extension to LMAC, we combine the time slot protocol and different frequency domains to let more nodes participate in the communication process. The idea is to let the nodes that cannot communicate due to maximum connectivity use another frequency domain. This will avoid conflicts with the nodes that already have right to communicate. In the frequency assignment process we introduce the following roles:

- **Sink**: The Sink is the connection between the users of the network and the network itself. Users of the network send queries to and collect the sensor readings from the WSN via the Sink. The Sink is the station which has wireless communication capability with the WSN.
- **Gateway**: The sensor nodes which are just one hop away from the Sink, i.e., which have direct communication link to the Sink.
- **Simple Node**: Other participant sensor nodes of the network.

The roles in the network is represented in Figure 3. We assume that during the frequency selection process, the nodes are static. Gateway nodes participate in the frequency selection process. They use the same simple approach used in time slot selection. All the Gateways maintain vectors of length equal to the number of frequencies for storing the occupied frequencies within the

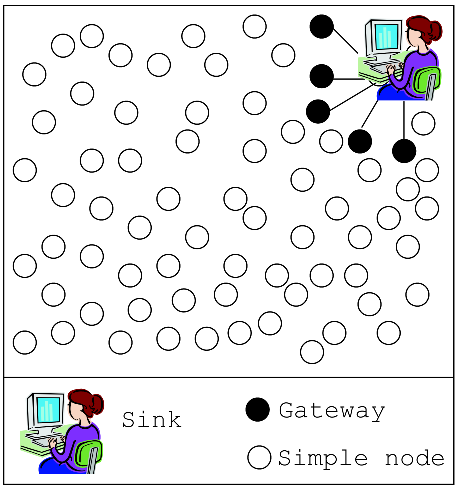

Fig. 3. Roles in the Network

2-hop neighborhood and local occupied frequencies to identify the frequencies controlled by the neighbors. Two nodes which are 1-hop neighbors of the Sink are at most 2 hops away from each other. So, the simple algorithm guarantees for selection of different frequencies for all the Gateways. One could have used a central algorithm in which the Sink assigns the frequencies to the Gateways. However, the Sink is not aware of the communication patterns and connectivity of all the nodes, globally. Instead, the simple collaborative approach is used.

4.1 Clustering

Gateways control the occupied frequencies, and make a selection from the free frequencies. If no free frequency is available, they give up the Gateway role and wait for the packets sent by the other Gateways like the simple nodes. At the network setup there is a frequency selection interval in which Gateways should finish the frequency selection process and the simple nodes do not process any packets. During this period, nodes communicate on the same frequency. After this interval, Gateways start broadcasting messages in which their frequency information is encoded. After broadcasting the frequency information, they switch to the controlled frequency. We assume that the hardware of the nodes is capable of switching between different radio frequencies. The frequency selection algorithm is represented in Figure 4.

The simple nodes that receive the frequency information decide to join that cluster if they do not belong to any cluster. There are 2 different decision options for the nodes. The nodes join the frequency whose packet is received the first. Or, the nodes can listen one frame interval and decide to join the cluster which seems to be the least crowded. The second option is possible if the node received

```
controlled_frequency - NO_VALUE
If (distance_to_sink==1)
   node_role = Gateway
   while(frequency_interval)
   do
      select a frequency
      If the frequency conflicts, select another
   done
   if(controlled_frequency == NO_VALUE)
      node_role - simple_node
else
   node_role - simple_node
   if( a frequency packet is received )
      swicth to the frequency
```

Fig. 4. The frequency selection algorithm

packets from the different frequency domains. After the frequency selection is over, nodes continue to communicate in the controlled frequency. The network view is represented in Figure 5. $F-\#$ represents the frequency the node is communicating with.

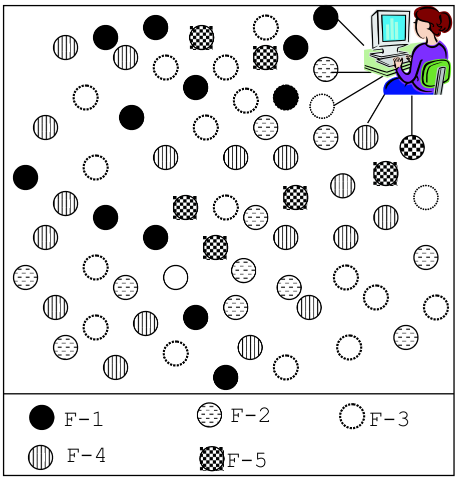

Fig. 5. Network view after frequency selection

We consider 3 different communication patterns. First is the communication from the WSN to the Sink, second is the communication from the Sink to the WSN and the last is the communication between a sensor node to another sensor. For the last type of communication, this method has one drawback. If two sensor nodes are closely placed to each other but belong to different frequencies, require to communicate, the data packets will have to travel all the path to the Sink.

Moreover the Sink will broadcast to find the path to the correct frequency-cluster to find the destination node. This method of communication will require a lot of nodes to take part in the communication and cause a lot of energy waste. Moreover the latency will increase because forwarding packets along many hops instead of just sending in 1-hop if only the nodes were communicating with the same frequency. In order to solve this problem, we introduce a new role of sensor nodes, the bridge nodes. The bridge nodes are the nodes that can communicate in more than 1 frequency. Consider Figure 6 for the solution of the bridge nodes. The bridge nodes have more than 1 time slot, each for different frequency. Node A has connectivity with both cluster X and Y. Node A should be communicating in frequency X while node B is transmitting, i.e., during node B's timeslot. Node A should switch to frequency Y during node C's timeslot. Node A can communicate in frequency X during node F's or node G's timeslot and in frequency Y during node D's or node E's timeslot. If a node's timeslot conforms to the conditions explained and it has connectivity to more than one frequency, then it can get the bridge node role to act as a switch between different frequencies.

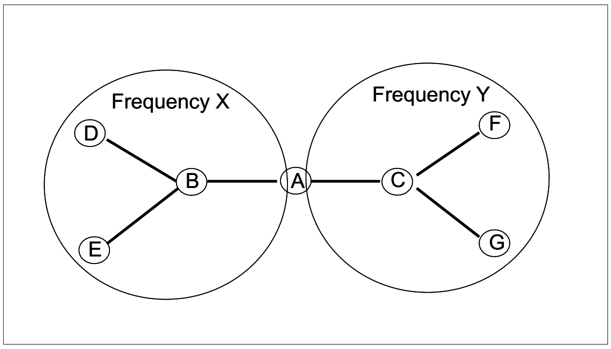

Fig. 6. Bridge Nodes

5 Experimental Results

In this section we give some experimental results about the number of active nodes (nodes that control a timeslot). We have carried out simulations in the Omnet++ environment [24]. The aim in doing experiments is basically to prove the concept of the frequency multiplexed LMAC algorithm to be working. Two different versions of LMAC algorithm, pure LMAC and frequency multiplexed LMAC are compared from two different aspects; number of active nodes and number of frequencies.

Fixed simulation parameters are tabulated in Table 1. A terrain of size 100*100 meters is used. Sensor nodes are deployed randomly within the terrain

Parameter Name	Value
Terrain Size	100*100 m^2
Transmission Range	40m
Sensor Node Deployment	Uniform
Mobility Characteristic	Static
Number of Nodes	25, 50, 75, 100, 125, 150
Number of Time Slots	32
MAC frame size	1 sec.
Number of Frequencies	2, 4, 8
Number of Runs	10000

Table 1. Simulation Parameters

and are assumed to be static during the simulation interval. Different number of frequencies, 2, 4 and 8, are used. Topology generator tool is used to deploy sensor nodes within the given dimensions of terrain size. We create 10000 random topologies and for each simulation run, either for LMAC or frequency multiplexed LMAC, the same topology is used.

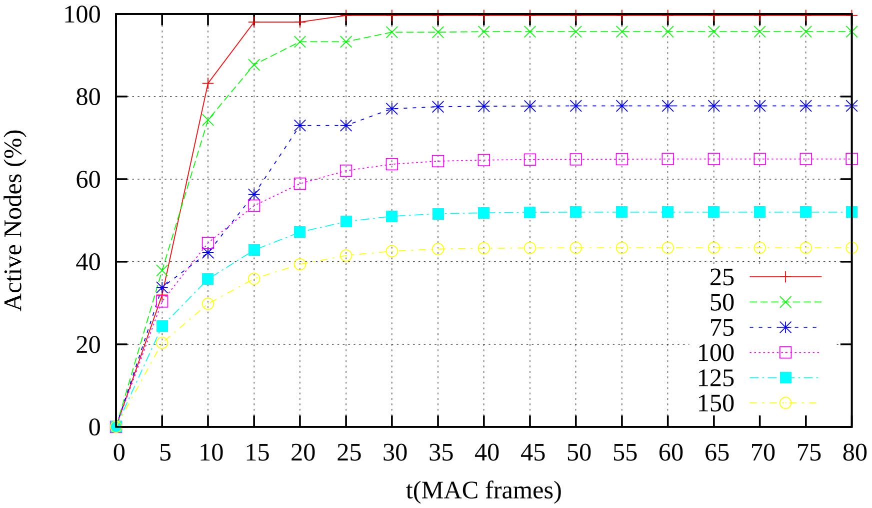

Fig. 7. Percentage of active nodes versus time

In Figure 7, the percentage of active nodes ([The nodes that have a timeslot/Number of nodes]*100) versus the number of MAC frames (time) is represented. For small number of nodes, 25 and 50, LMAC protocol performs well. Almost 100% of the nodes have timeslot. When the network gets denser, the percentage of the active nodes decreases. For 150 nodes, the performance is about 45%. Consequently, LMAC suffers from density. The performance is represented in Figure 8.

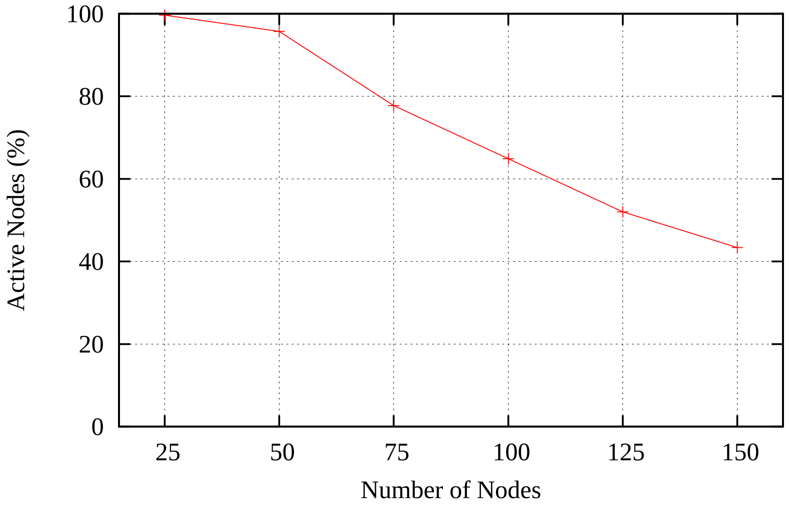

Fig. 8. Percentage of active nodes

In Figure 9, the number of active nodes in time is represented when a frequency multiplexed LMAC approach is used and the number of frequencies is just 2. Figure 10 is with 4 frequencies and Figure 11 is with 8 frequencies, respectively. Although the number of frequencies increases, the results are almost the same for 4 and 8 frequencies and still the performance is not 100%. This is due to the fact that the nodes are joining to the frequencies whose packet is received the first. So, some frequency clusters tend to be more crowded than the others.

One solution to this problem is to let the nodes listen for 1 MAC frame, analyze the denseness of the frequency clusters and then join the least populated cluster. Figure 12 represents the least crowded approach for 100 nodes. For 3 different number of frequencies, the performance reaches to 100%. In this method, nodes are evenly distributed among different frequencies.

6 Discussions and Conclusion

We have tackled the bandwidth resource management problem for WSN. The MAC protocols which grant access to the bandwidth may be inadequate in very dense environments. Time-slotted MAC protocol LMAC provides a limited time

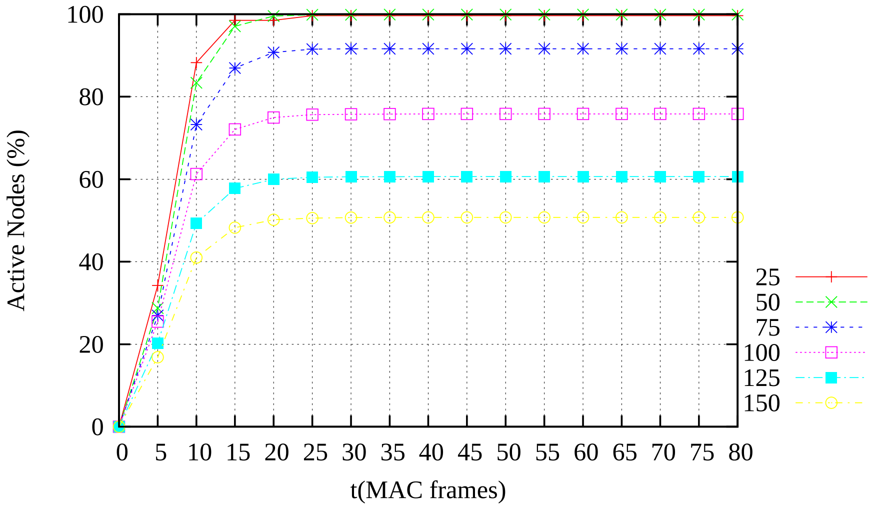

Fig. 9. Percentage of active nodes with 2 frequencies

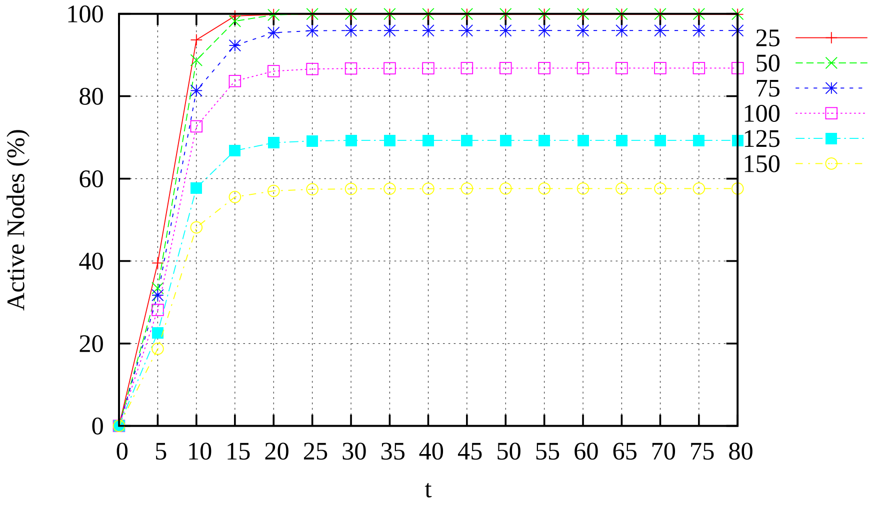

Fig. 10. Percentage of active nodes with 4 frequencies

domain. We extend LMAC by multiplexing the fixed time domain with frequency domain. The proposed method increases the number of available timeslots by a factor of the number of available frequencies. Simulation results show that, frequency multiplexing has the effect of increasing the capacity up to 100%.

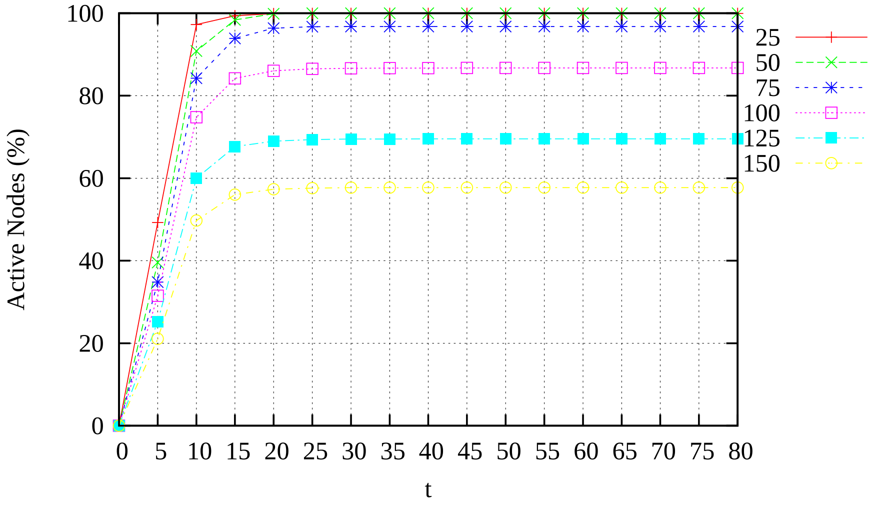

Fig. 11. Percentage of active nodes with 8 frequencies

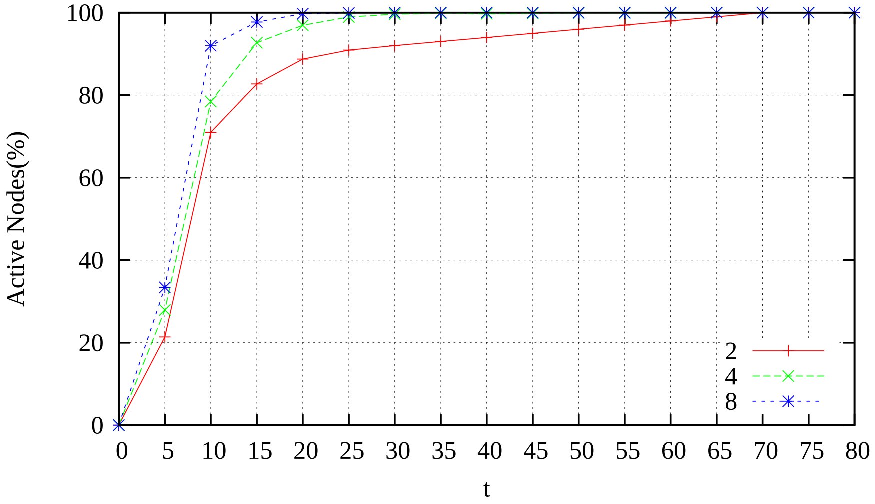

Fig. 12. Percentage of active nodes with 100 nodes with the least crowded method

The current state of the work improves the performance of LMAC in a static environment in terms of the active nodes. After the encouraging results of the simulations, we will explore the time-delay issue of this solution by the introduced bridge node role. Frequency reuse patterns will be introduced. Moreover, the performance will be tested against some mobility patterns.

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