Efficient Time-Based Topology-Dependent Scheduling for Radio Packet Networks*

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Abstract- In *Radio Packet Network (RPN)*, unconstrained transmission may lead to *collision* of two or more packets. *Time Division Multiple Access (TDMA)* protocol is a common used protocol to schedule collision-free transmission for such networks. TDMA transmission allows a number of users to access a single radio channel without interference by allocating unique time slots to each user. In TDMA network, time is divided into frames and a frame consists of time slots. For networks where each node is a neighbor for all the other nodes, each node should assign a different time slot in TDMA frame to transmit in it to have collision-free transmission. Typically, those time slots are ended by *guard times* for propagation delays. Those guard times are fixed for all time slots regardless the actual needed propagation delays.

In this paper, we propose a topology-dependent algorithm that automatically schedules collision-free channel access and specify the time instant when a node is to send a packet. We use *variable* guard times, instead of the fixed ones, calculated using the actual needed propagation delays between sources and destinations. We show that with such scheduling algorithm, a 90% saving in the original guard times could be achieved that increases the network utilization by about 10%.

1 Introduction

With the advances in wireless technology, *Radio Packet Network (RPN)*, where the network nodes share a common transmission channel, has received considerable attentions. In such networks, unconstrained transmission may lead to *collision* of two ore more packets. A collision is an overlapping in time of the transmission of two or more packets at the destination node resulting in reception of damaged packets. To avoid collision between network nodes in order to increase network utilization, save nodes energy, and reduce packet delays, network nodes must be assigned non-overlapped transmission periods in such way that the neighboring nodes can successfully transmit packets with no collision. The problem of assigning time slots to nodes is commonly known as *scheduling* or *slot assignment* problem.

Algorithms and protocols have been developed to schedule collision-free packet transmission for radio networks. *Time Division Multiple Access (TDMA)* protocol is commonly used to schedule collision-free transmission. TDMA transmission allows a number of users to access a single radio channel without interference by allocating unique *time slot(s)* to each user. In TDMA network, time is divided into frames and a frame consists of time slots. A schedule must guarantee that each user who needs to transmit will be assigned slot(s) in the frame. Any two stations for which their transmissions may result in collision must be scheduled to transmit at different time slots.

Typically, TDMA scheduling algorithms focus on the multi-hop radio networks ([2], [3], [6], [9]) . The objective is to find the slot assignment that reduces the TDMA frame size to its minimum by maximizing the reusable frame

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slots. In networks where nodes are located in the vicinity of each other (fully connected networks), each node need to transmit is assigned to a different time slot in the TDMA frame to have collision-free transmission. For example, if n nodes need to transmit, TDMA frame simply will contain n time slots as shown in Figure 1. Such configuration is required for some network models. For example, some sensor networks may require a set of sensor nodes within a single vicinity to report observations periodically to another set of sensors within the same vicinity ([10], [7]).

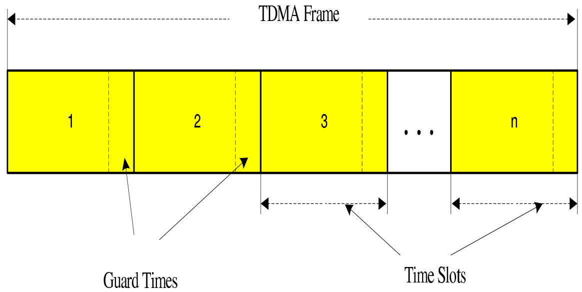

Figure 1: Packet transmission on shared medium

In Figure 1, each time slot is ended with *guard time* such that no node can transmit in this time. Guard time is used to allow the transmitted data to propagate to the destination node with no interference with other transmissions. That time period is fixed over all the time slots regardless of the distance between the source node and the destination node of the transmission using that slot. It is calculated to be the time needed for propagating a packet over the *network diameter*, which is the maximum distance between any two nodes in the network. With the increase in radio transmission rates[1] and ranges, guard times consume a significant amount of the network bandwidth that affects network performance. Figure 2 shows the utilization of a network, calculated as the percentage of the time needed to transmit data packets over the sum of the data packet transmission times and the guard times, versus data transmission rate for different packet sizes and different network diameters (transmission ranges).

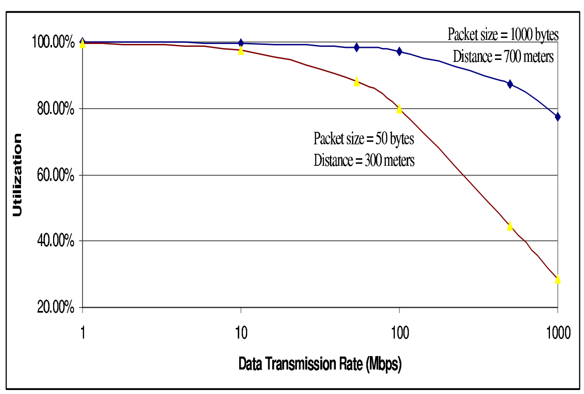

Figure 2: Network Utilization

In this paper, we focus on the problem of scheduling collision-free transmission of a node to neighbor nodes without any other packet interfering its transmission. We propose an efficient topology-dependent slot-less scheduling algorithm that automatically schedules collision-free channel access. Instead of using fixed guard times, we use variable guard times based on the exact propagation delay required between source nodes and destination nodes and specify the time instant when a node may is to send a packet. We show that with proper schedule of the transmissions, up to 90% of the typical fixed guard times will be eliminated.

The main contributions of this paper:

[1]Wireless standard 802.11 increased from 2Mbps to 11Mbps(802.11b). The new 802.11a standard is 54Mbps

- We formalize the transmission scheduling problem for fully connected radio packet networks. We show how the problem is reduced to the well known problem *Asymmetric Traveling Salesman Problem*.
- We present details of our simulation comparing our technique to the typical one. The simulation shows that our scheduling technique outperforms the current existence technique by a wide margin.

The paper is organized as follows. In section 2 we present the notations used and the problem formulation. We follow that with a detailed example to highlight the main idea behind our approach then the solution is formalized. Section 3 includes our simulation models and the simulation results. In section 4 a discussion about the previous related work is given. We conclude with section 5 which contains our concluding remarks and future work.

2 Efficient Time-based Topology-dependent Scheduling

2.1 Notations and Problem Formulation

In this paper, the following notations and definitions are used:

- $\{N_1, N_2, ..., N_n\}$ is a set of n *immobile* nodes located within an area A.
- The on-board clocks of all the n nodes are absolutely synchronized[2].
- D_{ij} is the propagation delay between node N_i and node N_j where $1 \leq i, j, \leq n$.
- D_A is the maximum propagation delay. This indicates that $D_A \geq D_{ij}$ for all i and j.
- The radio range of each node covers the whole area A (fully connected network).
- P_{ij} is the packet transmitted from node N_i to node N_j.
- The communication load of the network consists of m packets to be transmitted. For each packet, the source node and the destination node is given.
- S_{ij} is the time required for transmitting P_{ij}.
- $T_{i_1j_1}, T_{i_2j_2}, ..., T_{i_kj_k}, ..., T_{i_mj_m}$ are the *time points* in time space assigned by the *scheduler* to start transmitting packets $P_{i_1j_1}, P_{i_2j_2}, ..., P_{i_kj_k}, ..., P_{i_mj_m}$ respectively. The subscript k indicates the k^{th} time point that is assigned to the transmission of packet $P_{i_kj_k}$.
- $\{GT_k : k = 1..m-1\}$ is the *guard time*[3] needed to guarantee no interference between the k^{th} transmission of packet $P_{i_kj_k}$ and the consecutive $(k+1)^{th}$ transmission that is corresponding to packet $P_{i_{k+1}j_{k+1}}$. GT_k is calculated as follow:

$$GT_k = T_{i_{k+1}j_{k+1}} - (T_{i_kj_k} + S_{i_kj_k}) \tag{1}$$

- In TDMA approach, all guard times $\{GT_k : k = 1..m-1\}$ are assigned to a fixed value. We refer to such approach as *fixed guard time* approach. We use GT^{fixed} notation to refer to any of those guard times. We refer to our approach as *variable guard time* approach as the guard times will have different values from each others. We use $GT^{variable}$ notation to refer to any of those guard times.

[2] Clock synchronization can be achieved via the use of GPS or through the exchange of synchronization messages [11]. Such capabilities are implemented in wireless nodes such as Acoustic Ballistic Module from SenTech Inc. [1].

[3] Although the guard time could be assigned negative value as will be shown later, we still use the term as time needed to guard the consecutive transmission packets.

Given the above definitions, the total time needed for transmitting the m packets is:

$$T_{total} = \sum_{k=1}^{m} S_{i_k j_k} + \sum_{k=1}^{m-1} GT_k \tag{2}$$

and the network utilization (U) is defined as:

$$U = \frac{\sum_{k=1}^{m} S_{i_k j_k}}{\sum_{k=1}^{m} S_{i_k j_k} + \sum_{k=1}^{m-1} GT_k} * 100 \tag{3}$$

It is required to find the optimum time points for the packet transmissions that maximizes network utilization by minimizing the guard times ($\sum_{k=1}^{m-1} GT_k$) needed to prevent interference between the transmissions.

2.2 Two Packets Example

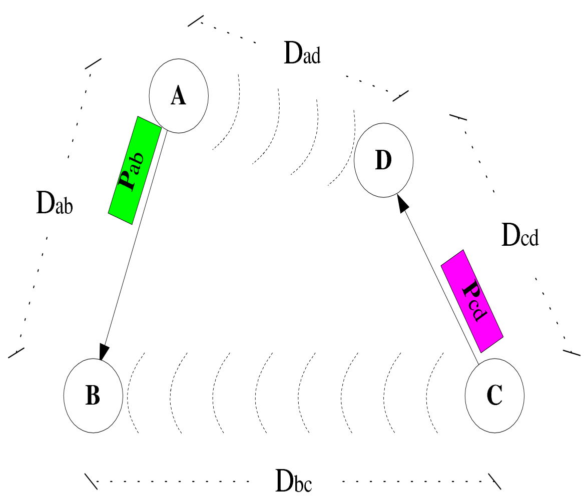

Figure 3: Two transmissions scheduling scenario

In this section, we use a simple two packet transmissions example, shown in Figure 3, to illustrate the required conditions of guard times to eliminate the interference between packet transmissions. In Figure 3, node **A** sends packet P_{ab} to node **B**, and node **C** sends packet P_{cd} to node **D** where all the four nodes are in the range of each other. D_{ab}, D_{bc}, D_{cd}, and D_{ad} are the propagation delays. The guard times are used to avoid any possible interference between the transmission of packets P_{ab} and P_{cd} at the receivers **B** and **D**. In other words, assuming P_{ab} will be transmitted first, we want the last bit of P_{ab} to be received by **B** before the first bit of P_{cd} reach **B**. Also, we want **D** to receive the first bit of P_{cd} after the last bit of P_{ab} reach **D** as in Figure 4. Other times of interest in this discussion are also shown in Figure 4.

Using the notation defined in Section 2.1 and the timing diagram in Figure 4, assuming packet P_{ab} is transmitted first before Packet P_{cd}, we have:

- Node **A** start transmitting packet P_{ab} at time t_0.
- Node **B** will receive the last bit of packet P_{ab} at $t_3 = t_0 + S_{ab} + D_{ab}$.
- t_{10} is the start time of transferring packet P_{cd} at node **C**.

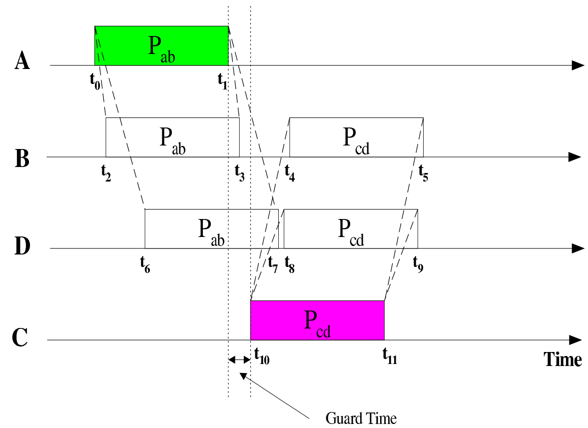

Figure 4: Timing diagram for Figure 3

- Packet P_{cd} will be propagated and reach node **B** at time $t_4 = t_{10} + D_{bc}$.
- In order to have no interference between packet P_{ab} and packet P_{cd} at receiver **B**, the following should hold:

$$\begin{aligned} t_4 &> t_3 \\ \Rightarrow t_{10} + D_{bc} &> t_0 + S_{ab} + D_{ab} \\ \Rightarrow t_{10} &> t_0 + S_{ab} + D_{ab} - D_{bc} \end{aligned} \tag{4}$$

- At the same time at node **D**, the last bit of packet P_{ab} will be received at time $t_7 = t_0 + S_{ab} + D_{ad}$, and the first bit of packet P_{cd} will be received at time $t_8 = t_{10} + D_{cd}$.
- To have no interference between the packets the following should hold also:

$$\begin{aligned} t_8 &> t_7 \\ \Rightarrow t_{10} + D_{cd} &> t_0 + S_{ab} + D_{ad} \\ t_{10} &> t_0 + S_{ab} + D_{ad} - D_{cd} \end{aligned} \tag{5}$$

- In order to have no interference between the transmission of packets P_{ab} and P_{cd}, inequalities 4 and 5 should hold. Which mean that:

$$\begin{aligned} t_{10} > \quad & t_0 + S_{ab} \\ & + max(D_{ab} - D_{bc}, D_{ad} - D_{cd}) \end{aligned} \tag{6}$$

- From above inequality, $max(D_{ab} - D_{bc}, D_{ad} - D_{cd})$ is the guard time needed ($GT^{variable}$) to eliminate any interference between the two transmissions. Since the values of D_{ab}, D_{bc}, D_{ad}, and D_{cd} range from 0 to D_A, the value range of the guard time in general is[4]:

$$-D_A \quad \leq GT^{variable} \leq \quad D_A \tag{7}$$

[4] A negative value of GT_k means that the $(k+1)^{th}$ transmission will start before the k^{th} transmission end.

The network utilization using this guard time is:

$$\begin{aligned} U &= \frac{S_{ab} + S_{cd}}{S_{ab} + S_{cd} + GT^{variable}} * 100 \\ &= \frac{S_{ab} + S_{cd}}{S_{ab} + S_{cd} + max(D_{ab} - D_{bc}, D_{ad} - D_{cd})} * 100 \end{aligned} \tag{8}$$

- In case of using TDMA approach, which is based on using maximum propagation delay as the fixed value for guard times, the guard time needed (GT^{fixed}) between the transmission of packet P_{ab} and the transmission of packet P_{cd} is $max(D_{ab}, D_{bc}, D_{ad}, D_{cd})$. Clearly, there is no interference between the two transmissions. The network utilization in this case is:

$$\begin{aligned} U &= \frac{S_{ab} + S_{cd}}{S_{ab} + S_{cd} + GT^{fixed}} * 100 \\ &= \frac{S_{ab} + S_{cd}}{S_{ab} + S_{cd} + max(D_{ab}, D_{bc}, D_{ad}, D_{cd})} * 100 \end{aligned} \tag{9}$$

- Comparing Equations 8 and 9, we find that we have reduced the guard time to the lowest possible value by eliminating the unnecessary delays and this increases the network utilization to its maximum value. For numerical example, assume the propagation delays (in seconds) of Figure 3 are: $D_{ab} = 10^{-6}, D_{cb} = 10^{-6}, D_{da} = 10^{-7}, D_{cd} = 10^{-8}$. We find that GT_V is equal to $9 * 10^{-8}$ while the GT_F is equal to $100 * 10^{-8}$. It is clear from these values that we have reduced the guard time by 91% of its original guard while maintaining the same property of preventing interference between the two transmissions.

2.3 General Problem Solution

In this section we show how the problem defined in Section 2.1 is reduced to *Asymmetric Travelling Salesman Problem (ATSP)*.

Assume three consecutive time points $T_{i_{k-1}j_{k-1}}$, $T_{i_k j_k}$, and $T_{i_{k+1}j_{k+1}}$ assigned to the transmission of packets $P_{i_{k-1}j_{k-1}}$, $P_{i_k j_k}$ and $P_{i_{k+1}j_{k+1}}$ respectively. Without any loss of generality, we assume the three transmitted packets are of equal sizes ($S_{i_{k+1}j_{k+1}} = S_{i_k j_k} = S_{i_{k-1}j_{k-1}} = S$). To have no interference between transmission of packets $P_{i_k j_k}$ and $P_{i_{k+1}j_{k+1}}$, the relation between the corresponding time points is:

$$T_{i_{k+1}j_{k+1}} = T_{i_k j_k} + S + GT_k \tag{10}$$

Also, the relation between the time points of the transmission of packets $P_{i_{k-1}j_{k-1}}$ and $P_{i_k j_k}$ to have no interference is:

$$T_{i_k j_k} = T_{i_{k-1}j_{k-1}} + S + GT_k \tag{11}$$

From Equations 10 and 11, we get:

$$\begin{aligned} T_{i_{k+1}j_{k+1}} = \; & T_{i_{k-1}j_{k-1}} + S + GT_{k-1} \\ & + S + GT_k \end{aligned} \tag{12}$$

Substituting GT_{k-1} and GT_k values with the lower bound of Inequality 7, we get:

$$\begin{aligned} T_{i_{k+1}j_{k+1}} = \; & T_{i_{k-1}j_{k-1}} + S \\ & + S - 2 * D_A \end{aligned} \tag{13}$$

From Equation 13, the guard time between the transmission of packet $P_{i_{k+1}j_{k+1}}$ and the transmission of packet $P_{i_{k-1}j_{k-1}}$ is $S - 2 * D_A$. In order to have no interference between those two transmissions, the following condition should hold[5]:

$$S - 2 * D_A \geq D_A$$
$$\Rightarrow D_A \leq \frac{1}{3} * S \tag{14}$$

With the condition[6] in Inequality 14, it is straightforward to conclude that there is no interference between the transmission of packet $P_{i_{k+1}j_{k+1}}$ and the transmission of packets $P_{i_1j_1}, P_{i_2j_2}, ..., P_{i_{k-1}j_{k-1}}$ for all $k = 2..m-1$. In consequence, the guard times $\{GT_k : k = 1..m-1\}$, where GT_k calculation is based only on the propagation delays of the consecutive transmissions k^{th} and $(k+1)^{th}$, are sufficient to guarantee no interference between the m transmissions.

Now, for the transmission of packets P_{ab} and P_{cd} in Figure 3 which are assigned to two consecutive time points (T_{ab} and T_{cd}). From Section 2.2, the relation between those time points is:
if P_{ab} is scheduled for transmission first,

$$\begin{aligned} T_{cd} &= T_{ab} + S_{ab} \\ &\quad + max(D_{ab} - D_{bc}, D_{ad} - D_{cd}) \end{aligned} \tag{15}$$

and *if P_{cd} is scheduled for transmission first,*

$$\begin{aligned} T_{ab} &= T_{cd} + S_{cd} \\ &\quad + max(D_{cd} - D_{ad}, D_{bc} - D_{ab}) \end{aligned} \tag{16}$$

Using equations 15 and 16, we find that the guard time value between two transmission depends on the relative order of these two transmissions. We represent the guard time value between the two transmissions as the *guard graph* shown in Figure 5.

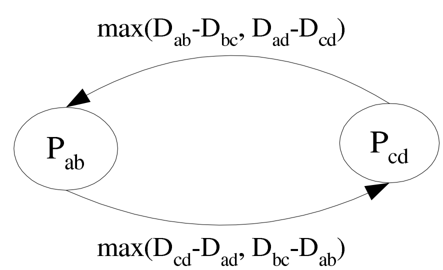

Figure 5: The guard graph for two transmissions

Figure 5 shows that if the transmission of packets P_{ab} and P_{cd} are assigned to two consecutive time points, then if P_{ab} is scheduled for transmission first, the guard time value is $max(D_{ab} - D_{bc}, D_{ad} - D_{cd})$. On the other hand if P_{cd} is scheduled for transmission first then the guard time value is $max(D_{cd} - D_{ad}, D_{bc} - D_{ab})$.

Let us consider the general case of m transmissions. The guard graph for the m transmissions is represented by a graph G = (V, E). The vertices $V = \{V_1, V_2, ..., V_m\}$ represent the m packet transmissions that would be assigned

[5]This condition is required when we only consider the interference between the transmission of two consecutive packets. In general case this condition can be eliminated but then we have to consider more complex interference which is out of scope of this paper.

[6]The Inequality 14 is easily satisfiable by the current wireless standards and implementations such as 802.11 [5].

to time points. The set of directed edges E represents the set of guard time needed between each pair of V when they could be scheduled to a two consecutive time points. More precisely, the two vertices V_i and V_j are joined by two directed edges E(i,j) and E(j,i) if they could be assigned to consecutive time points. The value of E(i,j) represents the guard time value needed to schedule transmission V_i first and then transmission V_j while the value of E(j,i) is the guard time value need for scheduling transmission V_j before transmission V_i. Since we assume there is no constraint in assigning the transmission of any two packets to two consecutive time points, G is a complete graph.

An auxiliary v_0 node is added to the graph G. The node v_0 is connected to each vertex v_i in V by two directed edges. One goes form v_0 to v_i and the other from v_i to v_0. The values of those v_0 edges are 0. Figure 6 shows the guard graph of the m transmissions where C_{ij} represents the value of edge E(i,j). With this representation, the

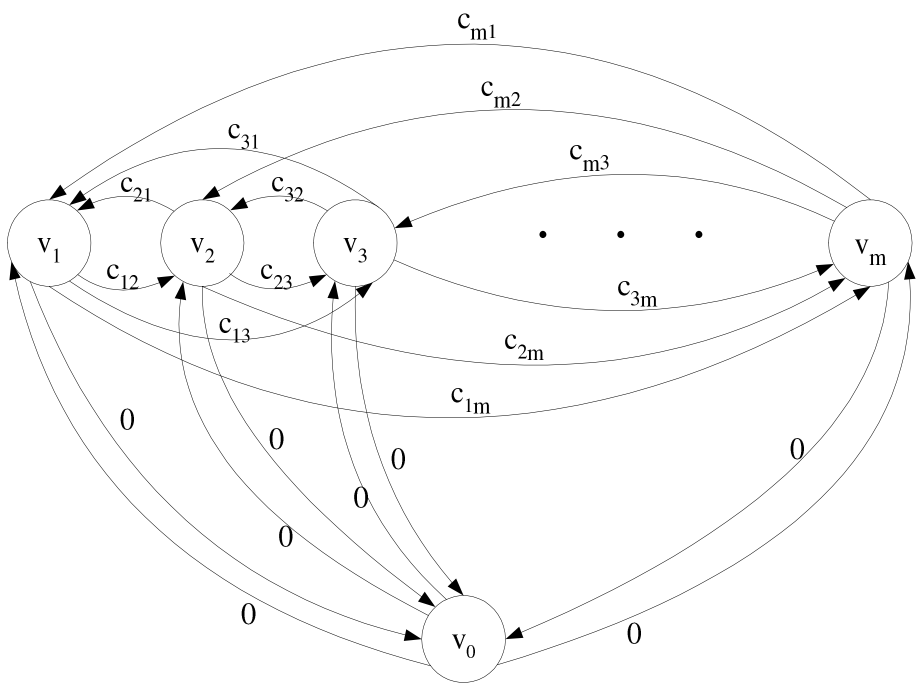

Figure 6: The guard graph for m transmissions

optimum time points scheduling is mapped to the problem of *finding the minimum value cycle that starts from v_0 and ends at v_0 passing by all the nodes just one time.* This is the well known problem *Asymmetric Traveling Salesman Problem (ATSP)* [8]. The solution of ATSP finds the minimum value Hamiltonian cycle of the graph. Given that the cycle start at the v_0 node, solving the ATSP will result in the optimum time points scheduling for the given m packet transmissions as shown in Figure 7.

ATSP is *NP-Complete* problem where no polynomial optimal solution exists for it. In order to establish the proof of concept for our approach, we use a simple heuristic ATSP algorithm, of order $O(m \log m)$, in our simulation.

3 Performance Evaluation

3.1 Simulation Model

In our simulation, we model a network of 100 nodes placed within a 300 meter x 300 meter area. Each node has a radio range that covers the whole area. In a typical simulation configuration, we select number of transmissions. The source and destination nodes of each transmission is randomly select. We use different configurations for different number of transmissions. In a simulation run, we construct the cost graph as shown in Figure 6 for the transmissions in each configuration. Then we apply the ATSP algorithm on each graph constructed to find efficient scheduling for

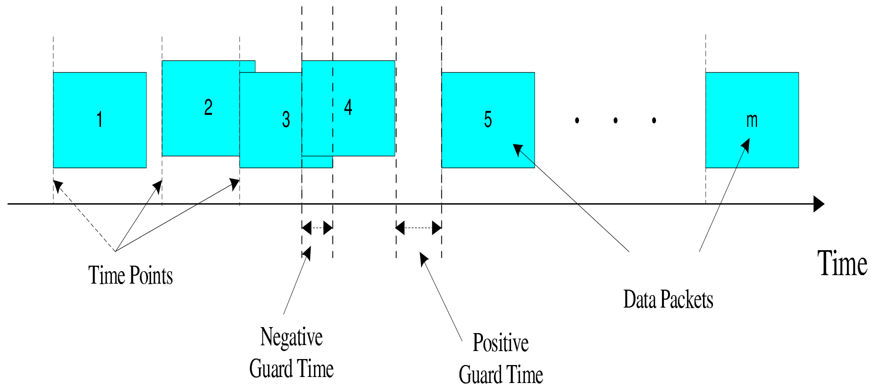

Figure 7: Scheduled m transmissions

the transmissions in each configuration. Each run is repeated 10 with new nodes generated within the area. We calculate the average of the all runs.

Two node distribution models are used in our simulation. *Uniform grid* model where the horizontal and vertical distances between consecutive nodes are 30 meters. The other model is the *random* model where there is no constraints on node locations.

The maximum possible distance between any two nodes in both models is $300\sqrt{2}$. In consequence, the maximum propagation delay [7]is $\sqrt{2} * 10^{-6}$sec. Figures 8 and 9 show statistics about the propagation delays (D_{ij}) used in each configuration in our simulation for both network models.

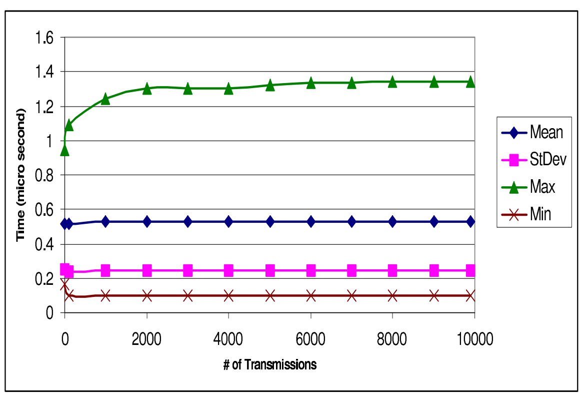

Figure 8: Propagation delay statistics for uniform grid network model

3.2 Simulation Results

Figures 10 and 11 show the propagation delays used by the fixed guard times (the TDMA approach where GT_k is equal to D_A) and the variable guard times (generated in our approach), for both network models. We can see that the variable guard technique outperforms the fixed guard. From the figures, both techniques increase linearly with the number of transmissions in the network. From our simulation models, the slope of the fixed guard is 1.414 while the variable guard slope is 0.152. It is clear that the slope of the fixed guard is much smaller than the variable guard slope which indicates that our technique is more scalable than the fixed guard technique.

[7]Using the signal transfer speed $3 * 10^8$ meter/sec.

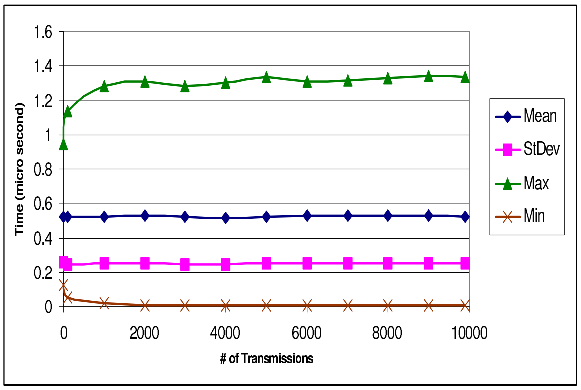

Figure 9: Propagation delay statistics for random network model

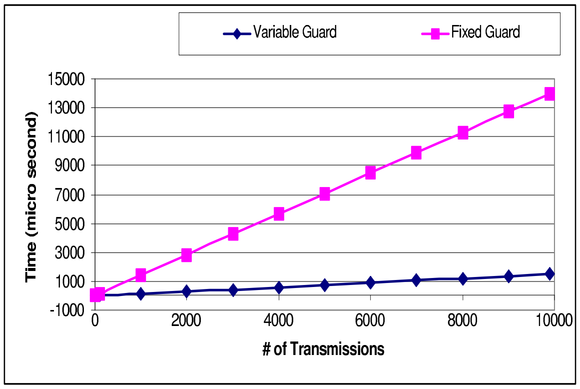

Figure 10: Propagation delay for uniform grid network model

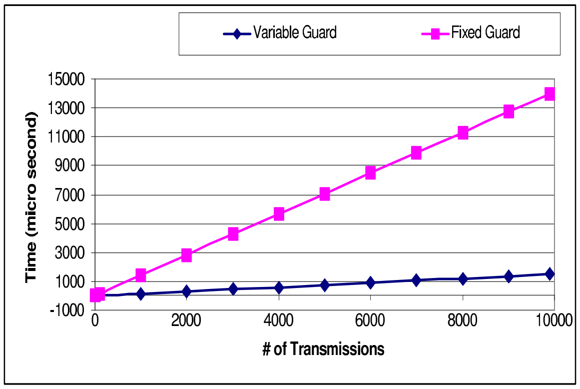

Figure 11: Propagation delay for uniform network model

For different data transmission rates and packet sizes, the network utilization using both techniques are shown in figures 12 and 13 for both models. As we can see, variable guard technique results in a higher network utilization than the fixed guard technique depending on the network configuration. In our network model, the network utilization is increased by about 10%. This percentage is clearly a function of the parameters of the model.

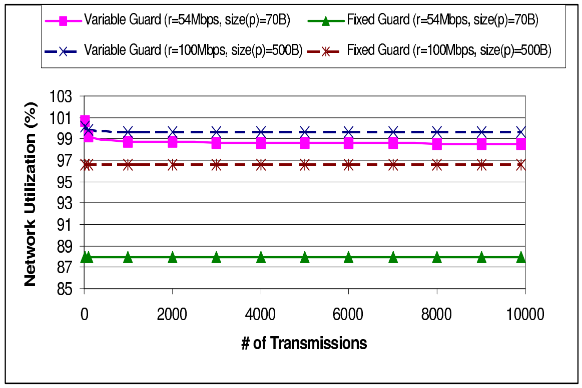

Figure 12: Network utilization for uniform grid network model

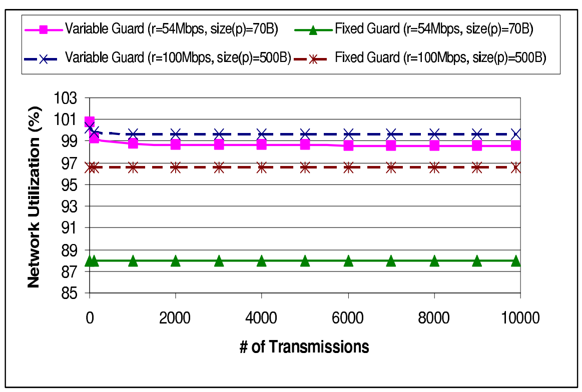

Figure 13: Network utilization for random network model

For the small network size (tens of nodes) in figures 12 and 13, we find the network utilization is more than 100%. From Equation 3 we conclude that the guard times must be added to a negative value. In consequence, this indicates that each node, on average, starts its transmission before the previous node finishes its transmission.

4 Related Work

In the following, we discuss some of the relevant papers that has appeared in the literature. As mentioned in Section 1 typical TDMA scheduling algorithms focus on the multi-hop radio networks. The objective is to find the slot assignment that reduces the TDMA frame size to its minimum by maximizing the reusable frame slots.

In [3] the authors show that the problem of finding the optimal broadcast scheduling in multihop radio network is NP complete by mapping it to the well-known NP-complete problem of finding maximum cardinality independent sets of nodes in a graph. A heuristic centralized algorithm is proposed that runs in polynomial time and results in efficient (maximal) schedules. Also a distributed algorithm is proposed that achieves the same schedules.

The problem of link and broadcast scheduling for multihop broadcast networks were studied in [9] for both arbitrary and restricted networks. By using the notion of the thickness of a graph, which is the minimum number of planar graphs into which a given graph can be partitioned, they showed that for a graph having thickness θ and a maximum vertex degree of ρ, the worst-case number of slots used by their proposed algorithms is proportional to $\theta^2\rho$ for a link scheduling and proportional to $\theta\rho$ for broadcast scheduling. The experimental model showed that the algorithms described used, on the average, roughly 8% (10%) fewer slots than did previously existing link scheduling (broadcast scheduling) algorithms.

Paper [6] presented an efficient broadcast scheduling algorithm, which is based on the sequential vertex coloring method, to minimize the frame length and maximize the channel utilization in order to achieve the lower time delay.

A topology transport protocol is proposed in [2]. A time slot allocation algorithm that schedules transmissions independently of network topology changes was presented. The algorithm was shown to guarantee conflict-free operation under any frequency of change as long as a maximum bound on the number of nodes and neighbors is observed in the network.

A Dynamic slot allocation mechanism for indoor environment is proposed in [4]. In that system, the base station uses uplink channel measurements to intelligently construct future frames. It was shown that the problem of performing optimal dynamic slot allocation under minimum signal-to-interference-plus-noise ratio (SINR) constraint is NP complete. A number of Heuristic slot allocation algorithms with varying complexity were introduced.

5 Conclusion

In this paper, we presented an efficient topology-dependent scheduling algorithm for radio packet networks. In our mechanism, we eliminated the unnecessary delays introduced by the fixed guard times separating packet transmissions. We showed that the optimum scheduling, which result in the minimum delays and higher network utilization, is NP complete. With simple heuristic algorithm the simulation results showed that, up to 10% increase in the network utilization when compared with the traditional method of using fixed guard times for our network models.

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