Comparison Between Graph-Based and Interference-Based STDMA Scheduling

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ABSTRACT

Spatial reuse TDMA is a fixed assignment access scheme for multi-hop radio networks. The idea is to increase network capacity by letting several radio terminals use the same time slot when the interferences caused are not too severe. We consider two methods of generating traffic controlled reuse schedules. One method uses full knowledge of the interference environment to generate schedules. The other method uses a graph representation of the network, assuming limited knowledge of the interferences. By simulations, we evaluate the proposed methods in terms of average delay and throughput.

The simulation results indicates that the network performance of the graph-based scheduling may suffer compared to the interference-based scheduling, depending on how the graph is created.

In a stationary situation, or temporary stationary situation, where knowledge of the full interference environment can be assumed, interference based scheduling can improve the network capacity by up to one third, thereby being worth its increased complexity.

1. INTRODUCTION

We consider a radio network where a number of radio units are spread out in the terrain. If the received signal power is sufficient in relation to noise and interferences, it is assumed that any two radio units can communicate, i.e., establish a *link*. In a multihop network, the power consumption can be kept low, and area coverage is achieved by letting messages be relayed over one or several intermediate nodes. Distributed multihop radio networks are often referred to as ad hoc networks.

One problem in a radio network is the interferences caused by simultaneously transmitting nodes. These conflicts occur if the received signal is too weak compared to the interfering signals. An important issue is therefore to design efficient Medium Access Control (MAC) protocols that control the use of the channel. Such a MAC protocol is Spatial Reuse TDMA (STDMA), which is an extension of TDMA where the capacity is increased by spatial reuse of the time slots. An STDMA schedule describes the transmission rights for each time slot.

The concept of spatial reuse channel access schedule for multi-hop packet radio networks was formalized by Nelson and Kleinrock in [7]. In the literature, various algorithms for generating reuse schedules have been proposed. Centralized algorithms [4, 6] as well as distributed algorithms [2, 3],have been proposed for mobile ad hoc networks. Most work described in the literature have in common that the reuse schedule is designed from a graph model of the network. We adopt an alternative interference model suggested by Zander [10], where the signal-to-interference ratio (SIR) is used to describe interferences in the network. We say that a schedule is conflict free in terms of SIR, if the SIR does not drop below a certain threshold.

A reuse schedule obtained from a traditional graph approach may result in serious interferences in terms of SIR. A graph consists of a set of *nodes* and a set of *edges* connecting pairs of nodes. To obtain a graph representation of a radio network, each radio terminal is represented by a node containing the attributes of the radio terminal. Also the set of edges must be chosen. If we choose as edges only the communication links with a signal-to-noise ratio so that they can provide reliable communication, serious interferences are likely to occur. The reason for this is that signals that are too weak to provide reliable communication still can cause strong interferences. Graph methods can be applied when the graph representation is chosen to include also links with signal-to-noise ratio below the threshold for reliable communication as edges, i.e. so called *interfering edges*. The concept of interfering edges is described for *channel assigned* schemes in [8]. We suggest such a graph scheduling method where the graph representation is chosen so that the remaining interferences are moderate. One advantage of this approach is that any graph based assignment algorithm can be applied.

The other approach we consider uses the full interference environment. One such method was suggested for STDMA in [9]. This approach leads to schedules that are conflict free in terms of SIR.

To compare the above approaches we use schedules generated as described in [5]. Important features of this algorithm is that it fully compensates for varying traffic loads of the links in the network and uses a priority system when slots are assigned.

2. INTERFERENCE BASED SCHEDULING

Here we describe the interference-based model of a radio network. The network is represented by a set of nodes $\mathcal{V}$ and the basic transmission path-loss $L_b(i,j)$ between any two

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distinct nodes $v_i, v_j \in \mathcal{V}$. For simplicity, we assume isotropic antennas.

For any two distinct nodes v_i, v_j, where v_i is the transmitting node, we define the *signal-to-noise ratio* (SNR) Γ_{ij} as

$$\Gamma_{ij} = \frac{P_i}{L_b(i,j)\, N_r}, \tag{1}$$

where P_i denotes the power of the transmitting node v_i, N_R is the noise level in the receiver.

We say that a pair of nodes v_i, v_j form a *communication link*, (i, j) if the signal to noise ratio (SNR) is not less than a *communication threshold* γ_C. That is, the set of communication links $\mathcal{K}$ in the network is defined as $\mathcal{K} = \{(i,j) : \Gamma_{ij} \geq \gamma_C\}$. For a set of links, $K \subseteq \mathcal{K}$, we define the *transmitting nodes* as $V_T(K) = \{v_i : (i,j) \in K\}$. For any link, $(i, j) \in K$, we define the *interference* as

$$I_K(i,j) = \sum_{v_k \in V_T(K) \setminus v_i} \frac{P_k}{L_b(k,j)}. \tag{2}$$

Furthermore, we define the *signal-to-interference ratio* (SIR) as

$$\Pi_K(i,j) = \frac{P_i}{L_b(i,j)(N_r + I_K(i,j))}. \tag{3}$$

Let us assume that any two radio units can reliably communicate a packet without error if the SIR is not less than a *reliable communication threshold* γ_R. A schedule S is defined as the sets X_t, for $t = 1, 2, \ldots, T$, where T is the period of the schedule. The sets X_t contain the links assigned time slot t. A schedule is called conflict-free if (3) holds for all receiving nodes in all sets X_t.

We say that a link (k, l) is *adjacent* to link $(i, j) \in K$ iff $\{i, j\} \cap \{k, l\} \neq \emptyset$. Furthermore, we define $\Psi(K)$ as the union of all adjacent links to the links in K. Furthermore, let us assume that a node cannot transmit more than one packet in a time slot and that a node cannot receive and transmit simultaneously in a time slot. This assumption can also be described such that a set of links K and the set of its adjacent links $\Psi(K)$ must be disjoint:

$$K \cap \Psi(K) = \emptyset. \tag{4}$$

The signal-to-interference criteria (3) gives the the following condition:

$$\Pi_K(i,j) \geq \gamma_R \quad \forall \quad (i,j) \in K. \tag{5}$$

If the above two conditions, (4) and (5), hold for a set of links $K \in \mathcal{K}$, we say that the set of links can *transmit simultaneously*.

3. GRAPH BASED SCHEDULING

The traditional approach in designing reuse schedules is to use a graph model of the network. Given a graph, a reuse schedule can be obtained by studying the set of edges.

We represent the radio network as a directed graph G_γ with a set of nodes $\mathcal{V}$ and a set of edges E satisfying the condition

$$(i,j) \in E \text{ if and only if } \Gamma_{ij} \geq \gamma\ .$$

The schedule is then designed from the graph G_γ. Interferences from other nodes are not taken into account. The traditional method for link assignment, given the set of edges E, is to say that two edges (i, j) and (k, l) can be assigned the same time slot if and only if:

- The nodes v_i, v_j, v_k, v_l are all mutually distinct,
- $(i, l) \notin E$ $(k, j) \notin E$.

The first criterion is based on that a node cannot receive and transmit simultaneously in the same slot. The second criterion is that a node cannot receive a packet while neighbouring nodes are transmitting.

Observe that the above criterions are not sufficient to guarantee that the assignment is conflict-free in terms of SIR. The assignments that fulfill the above two criterions do not necessarily fulfill the SIR condition (5). They may therefore not be able to *transmit simultaneously* according to our definitions. We illustrate this with a small example.

Example 1. To the left in figure 1 we see the edges obtained for a sample network by choosing the threshold γ_C to be 13 dB. Now, assume that links (2,4), (7,5) and (8,9) have been assigned the same time slot. This is possible according to the graph model of the network. If all of these nodes transmit at the same time, the SIR calculated at node 5 will only be 1.6 dB. This is because the SNR between node 8 and 5 is just below what is needed for communication and SNR between 7 and 5 is just above.

From the example, we see that the graph approach applied as above will result in serious interferences. However, graph based algorithms can still be useful. One method to avoid the serious interference levels shown in example 1 is to base the schedule on a graph where also node pairs with SNR less than γ_C are included as interference edges [8]. The edges with SNR lower than γ_C will, of course, not be assigned any time slots. They will only be used in the test criterion. By considering a graph G_γ and letting γ take a value γ_I smaller than γ_C, the set of edges will contain not only the links but also interference edges, which represents the case when the signal from one user is too weak to be used for communication but still is strong enough to interfere. We will call γ_I the *interference threshold*.

The choice of γ_I determines the remaining interference, as all transmissions in the time slot will add to the interference. By choosing the threshold for a communication link, γ_C, slightly greater than what is needed for reliable communication, γ_R, we assure that the communicating link can handle these remaining interferences. The following example illustrates this procedure.

Example 2. Consider our previous example. To the right in figure 1 we show G_γ with γ chosen to be 7 dB. The interference edges obtained, are illustrated with dashed lines. With this graph description we can see that the links $(2, 4)$ and $(7, 5)$ can not share the same slot, since the interference edge $(2, 5)$ exist. This means that interference violation in node 5 will be avoided.

In some cases the interference edges will prevent nodes from being assigned a time slot that could be assigned to the same slot without violating the SIR criterion. One such example is links $(10, 5)$, $(2, 1)$, and $(8, 6)$. These three links will not be allowed to share a slot since the interference edges $(2, 5)$ and $(8, 5)$ exists. However, the SIR values on all possible receiving nodes are above 10 dB. This is because the signal levels are so strong that quite strong interferences can be accepted.

The graphs G_{γ_C} and G_{γ_I} with a properly chosen γ_C and γ_I can now be used to generate a reuse schedule with any assignment algorithm taking a graph as a network model.

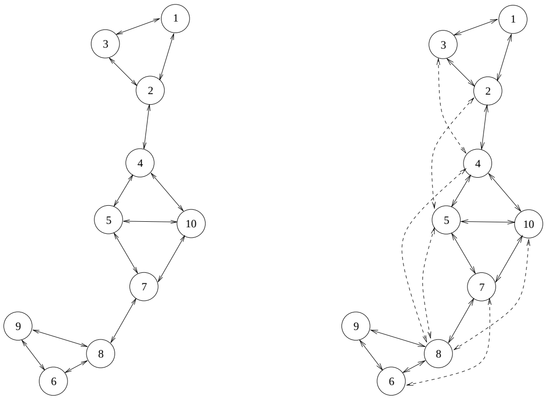

Figure 1: *Left:* The graph G_γ obtained for $\gamma = 13$ dB of a small sample network consisting of ten nodes. *Right:* The graph G_γ obtained for $\gamma = 7$ dB. To the right, interference edges are indicated with dashed lines.

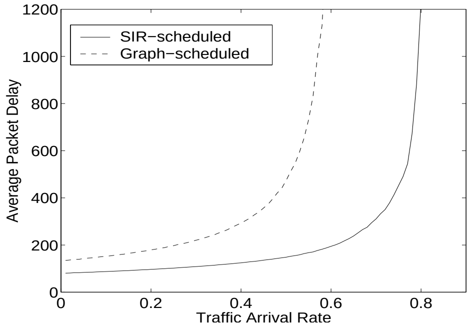

Figure 2: The figure shows the average packet delay for different arrival rates for a 40 node network. This is plotted for both a schedule based on the SIR-model and a schedule based on the graph-model.

4. PERFORMANCE EVALUATION

The relaying of traffic causes a considerable variation in the traffic of the links in a network. This will cause “bottle neck” effects at busy nodes with long packet delays as a result. To achieve large throughput, we have to use an efficient traffic-controlled schedule to compensate for this problem, see [5].

We assume a point-to-point traffic model, i.e. that a packet entering the network has only one destination. We assume that messages arrive to the network in packets of equal size, according to a Poisson process with mean λ packets per slot. Packets enter the network at entry nodes and exit the network at exit nodes. The entry and exit nodes are selected according to a uniform distribution.

In our evaluations we use the *average packet delay* as a performance measure. *Packet delay* is the time measured in time slots, from the arrival of a packet at the buffer of the entry node v_k to the arrival of the packet to the exit node v_l. Due to the relaying of packets the statistical properties of this random variable is complicated and an exact analytical analysis of the expected value is difficult [7]. In our analysis we have chosen computer simulations as evaluation method.

Since we study conflict-free schedules, we have to generate these conflict-free schedules based both on the SIR model and the two-level graph model with appropriate SIR. Remember from section 2 that a schedule is considered to be conflict free if the SIR is above a threshold γ_R. However, it is difficult to design a graph-based schedule to a certain minimum value of γ_R, since given a γ_R we have to find appropriate values of γ_C and γ_I such that the resulting SIR is as close to γ_R as possible.

If we have one strong interferer with an interference that lies just below the interference threshold the resulting SIR will at least have the value

$$\frac{\gamma_C}{1+\gamma_I}.$$

A simple choice here is to set γ_I to 0 dB. Then all remaining interferences will be weaker than the receiver noise. If we, for example, choose γ_C to be 10 dB our single interferer will give us a resulting SIR of 7 dB. For more than one strong interferer, we can get a lower resulting SIR. Of course, this is under the assumption that the communication link have a SNR close to the threshold γ_C.

Now, we can see that a very low value of γ_I (below 0dB) will even at a worst case scenario result in a SIR close to to the communication threshold. But this will also result in very many interference edges in the graph and thereby a very low spatial reuse. On the other hand, a high value of γ_I (close to γ_C) can result in very low SIR, even below 0dB independent on the choice of γ_C, although, it allows for high spatial reuse.

Without any further investigations we will use 10dB as the communication link threshold and 0dB as the interference threshold.

Since we have no perfect way of designing a graph-based schedule to a certain minimum SIR γ_R, the choices of γ_C and γ_I have to be made such that we are certain that the resulting SIR are equal to or higher than γ_R, thereby most often achieving a resulting SIR that are much higher than necessary (and of course the corresponding loss in spatial reuse).

SIR-based scheduling, on the other hand, can set its target SIR to γ_R and achieve a resulting SIR very close to its target. However, since we have not investigated the choices of γ_C and γ_I we ignore this fact and assume that appropriate values of γ_C and γ_I can be found to achieve the wanted γ_R in the comparison.

In order to do this, we will use γ_C and γ_I to be 10dB and 0dB in the generation of the graph-based schedule and use the resulting minimum value of SIR over all time slots for γ_R when we are generating the SIR-based schedule.

One example of how average packet delay varies with traffic for a network is given in figure 2.

We present simulation results for 100 networks of size 40 nodes. These networks have been generated with different connectivity by varying the location of the nodes and the transmitting power. However, all nodes in a network use equal transmitting power. Connectivity is the average fraction of the nodes in the network that can be reached by a node in one hop, i.e. $M/(N(N-1))$, where M is the number of directed links in the network.

To generate realistic networks, a terrain-data-based ground wave propagation model, Vogler’s five knife-edge model, has been used for the calculation of the basic transmission path-loss [1] between all pairs of nodes.

In the simulations we assume that the shortest route between two nodes has been used, i.e. packets between two nodes will always use the way which requires the least number of transmissions.

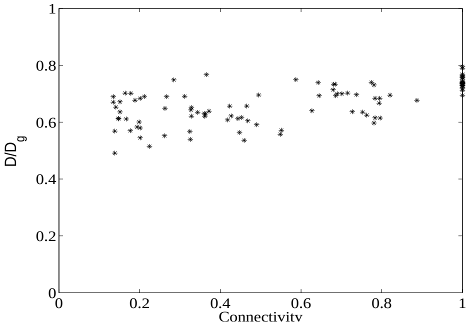

Figure 3: The fraction D/D_g of the average packet delay for SIR-based schedules and graph-based schedules plotted for different network connectivities. The relation is plotted for 100 networks of size 40 nodes.

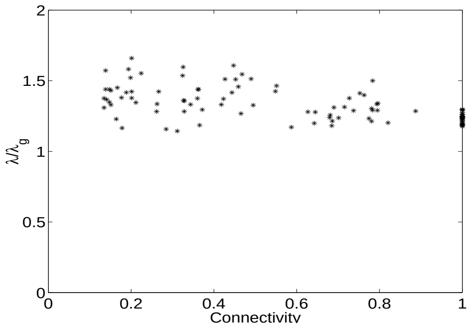

Figure 4: The fraction λ/λ_g of the throughput for SIR-based schedules and graph-based schedules plotted for different network connectivities. The relation is plotted for 100 networks of size 40 nodes.

5. SIMULATION RESULTS

In figure 3, the fraction D/D_g of the average packet delay D for SIR-based schedules and the average packet delay D_g for graph-based schedules is plotted. In figure 4 the corresponding fraction λ/λ_g for the maximum throughput is plotted. The graph-based schedules performs worse than the SIR-based schedules. For example, almost a third of the maximum throughput is lost in some cases.

To motivate why this is the case we plot the distribution of the minimum SIR of the time slots for both schedules for one of the networks. As can be seen the algorithm using the SIR-model manage to schedule its slots to a resulting SIR much closer to γ_R than an algorithm using the graph model. Since the graph-model have much less information of the network it has to behave more carefully in its assignment of time slot.

6. CONCLUSIONS AND COMMENTS

Our simulation results indicates that the network performance of the graph-based scheduling may suffer compared to the interference-based scheduling, depending on the SIR thresholds.

In order to achieve collision-free schedules, up to one third of the network capacity can be lost with the more careful graph-based scheduling due to limited information of the network. No clear dependence of the network connectivity has been observed.

Since the interference-based scheduling is very complex, it is difficult to use in distributed scheduling algorithms, which means that some form of model with limited information must be used. On the other hand, for the graph-based scheduling, it is necessary with more investigation of how to determine the thresholds used in the scheduling, as we otherwise might loose too much of the network capacity. In the stationary or temporary stationary case, where the knowledge of the full interference environment can be assumed, the SIR-model offers sufficient improvemnt to be worth its increased complexity.

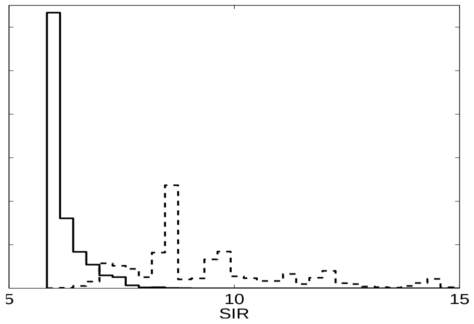

Figure 5: The figure shows the distribution of the minimum SIR of the time slots both for a graph-based schedule and for a SIR-based schedule.

7. REFERENCES

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