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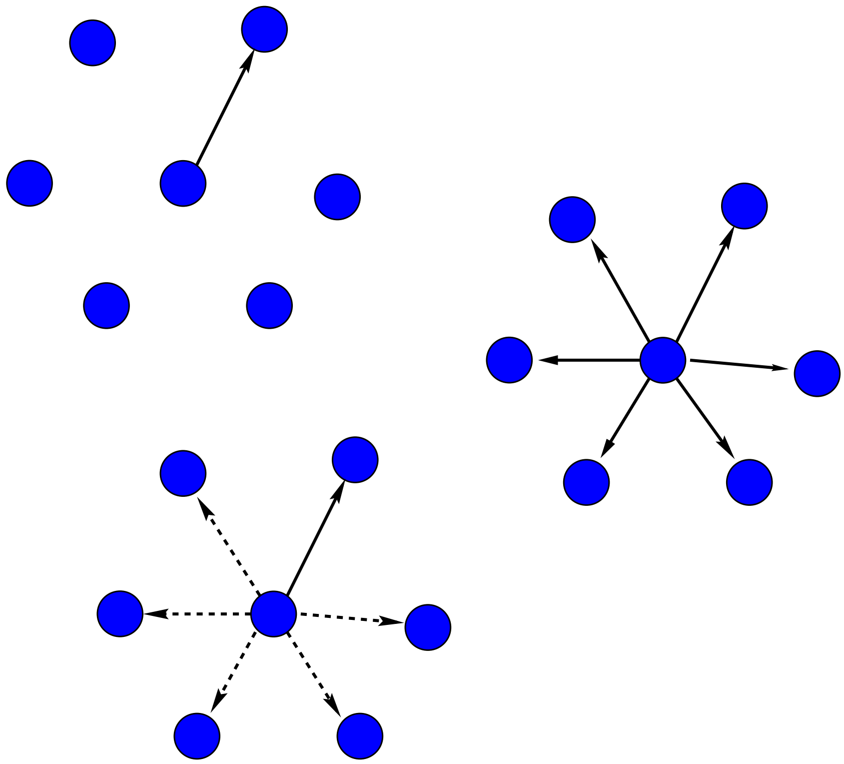
Jimmi Grönkvist

Assignment Methods for Spatial Reuse TDMA



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Assignment Methods for Spatial Reuse TDMA

Abstract

Spatial reuse TDMA is an access scheme for multi-hop radio networks. The idea is to increase capacity by letting several radio terminals use the same time slot when possible. A time slot can be shared when the radio units are geographically separated such that small interference is obtained. In reuse scheduling there are several alternative assignment methods, traditionally, transmission rights are given to nodes or to links, i.e., transmitter/receiver pairs. We present a comparison of these two approaches and show that both have undesirable properties in certain cases, e.g. link assignment gives a higher delay for low traffic loads but can achieve much higher throughput than node assignment. Furthermore, we propose a novel assignment strategy, achieving the advantages of both methods. Simulation results show that the proposed method can achieve the throughput of link assignment as well as the lower delay characteristics of node assignment for low traffic loads.

Keywords

STDMA, MAC, spatial reuse, radio network, multi hop, ad hoc

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Rapportens titel

Tilldelningsmetoder för STDMA

Sammanfattning

Spatiell TDMA är en accessmetod för radionät med flerhoppsfunktion. Grund idéen är att man ökar kapaciteten genom att låta flera radioterminaler använda tidluckan när det är möjligt. En tidlucka kan delas om det geografiska avståndet mellan dem är så stort att de ej skapar interferenser hos varandra. För STDMA finns flera olika alternativa tilldelningsmetoder. Vanligtvis ger man sändningsrättigheterna till noder eller länkar, dvs sändar/mottagarpar. vi presenterar här en jämförelse mellan dessa två och visar att båda har negativa egenskaper i vissa situationer. Till exempel så ger länktilldelning hög fördröjning för låg nättrafik men mycket högre genomströmning än nodtilldelning. Vi presenterar också en ny tilldelningsmetod med fördelarna hos båda tilldelningsmetoderna. Simuleringsresultat visar att den föreslagna metoden kan uppnå den höga genomströmningen hos länktilldelning och en lika låg fördröjningen som nodtilldelning vid lite trafik.

Nyckelord

STDMA, MAC, spatiell återanvändning, radionät, flerhopp, ad hoc

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Chapter 1

Introduction

In many situations fixed communication infrastructure cannot be relied upon for wireless communication, and where fast self-configurable networks must be installed quickly, e.g., emergency relief or military networks. A common feature of these networks is that they are not pre-planned, and area coverage is achieved by letting the radio units relay the messages, i.e. a multi-hop network. Distributed multi-hop radio networks are often referred to as ad hoc networks. One of the most challenging problems in ad hoc networks is to guarantee Quality of Service (QoS).

An important design issue is the Medium Access Control (MAC), i.e., how to avoid or resolve conflicts due to simultaneously transmitting radio units. Traditionally, MAC protocols for ad hoc networks are based on dynamic access methods such as carrier sense multiple access (CSMA), e.g., the IEEE 802.11 standard [1]. Although efforts have been made to guarantee QoS in CSMA-based MAC protocols, see e.g. [2], dynamic methods are inherently inappropriate for providing QoS guarantees.

One of the most important QoS parameters in many applications is delay guarantees, i.e., an upper bound on the time it takes to transmit a message from the source to destination or an upper bound on the variance of the delay (jitter). This is useful when transmitting delay sensitive traffic such as voice or video.

One approach where delay bounds can be "guaranteed" is time division multiple access (TDMA).

Unfortunately, this is usually inefficient in sparsely connected networks. However, due to the multi-hop properties, the time slots can often be shared by more than one user without conflicts in such network topologies.

To increase capacity one can therefore use spatial reuse TDMA (STDMA), which is an extension of TDMA where the capacity is increased by spatial reuse of the time slots, i.e., a time slot can be shared by radio units geographically separated so that small interference is obtained.

The problem is then to design STDMA schedules fulfilling required properties, e.g., minimizing delay or being able to update the schedules in a distributed fashion. An STDMA schedule describes the transmission rights for each time slot.

The problem of designing STDMA schedules is well addressed in literature. Centralized algorithms [3, 4] as well as distributed algorithms [5, 6, 7, 8] for mobile ad hoc networks have been proposed.

Previous work on STDMA generally investigates two types of assignment algorithms. Some assign transmission rights to nodes, i.e., a node can transmit to any of its neighbors in an assigned time slot. In others, transmission rights are assigned to links. In this case both transmitting and receiving nodes are determined in advance.

Examples of node assignment algorithms can be found in [9, 10, 3, 8], and link assignment algorithms in [5, 7, 4].

Furthermore, it has been shown that finding a minimum length schedule is NP-complete for both link and node scheduling [11, 12]. In [13], algorithms for both link and node scheduling are described focusing on the generation of short schedules, i.e., a schedule where all nodes or links are given a slot with as few time slots as possible. In [14], a more general description of the assignment problem is given. The different assignment methods are then seen as constraints in a unified algorithm for the assignment problem given in the paper.

However, it has not been shown which approach is preferable.

In this paper, we determine in what situations link or node assignment is preferable. Our result suggests that the connectivity of the network and the input traffic are sufficient parameters for determining which approach is preferable. Link assignment achieves higher throughput than node assignment. The gain in throughput increases with the size of the network and decreases with increased connectivity. However, this increase in throughput comes at a cost of higher delay for low traffic loads.

Furthermore, we propose a novel assignment strategy that achieves the higher throughput of link assignment without the cost of higher delay for low traffic loads. The strategy proposed is based on a link schedule, but where transmission rights are extended in the following way. Assume that a node is scheduled to transmit to a specific neighbor according to the link schedule. Now, if the node does not have a message in queue destined for this specific neighbor, the node is permitted to use the scheduled slot to transmit a message to another neighbor. Such transmissions will not always be conflict-free.

The result is as high degree of spatial reuse as link assignment, but at low traffic the same behavior as node assignment.

To determine whether a conflict has occurred, some sort of feedback information is required, but in any realistic radio system also a theoretically conflict-free schedule needs feedback information.

The method we suggest may be used in combination with any link assigned schedule, but for evaluation we consider schedules generated as described in [15]. Important features of this algorithm are that it fully compensates for the varying traffic loads of the links in the network and uses a priority system when slots are assigned.

In order to generally determine whether our method is preferable to node or link assignment, it should be compared with the best of all possible schedules for node and link assignment. Since this is not possible, however, the algorithm has been chosen based on simplicity rather than optimality. Nevertheless, the results from the simulation can be used as an indication of the properties of our proposed method.

We use an interference-based model of the network as suggested for STDMA scheduling in [16].

In this paper we focus on point-to-point traffic. Whether node or link assignment should be used is interesting essentially for point-to-point traffic. For broadcast or multicast traffic, node assignment has an obvious advantage to link assignment. Although our method would be interesting to compare with node assignment for broadcast traffic, we will leave this for future research.

The assignment methods are evaluated using simulations in terms of end-to-end delay and throughput for different network connectivity.

In section 2 our network model is described. In section 3 we determine the circumstances under which nodes or links may share a time slot. This is followed in section 4 by a closer description of our proposed method. Section 5 describes the evaluation parameters together with the network traffic model. In section 6 many properties of the new method are discussed, and section 7 presents some analytical results. In section 8, the simulation setup and simulation results are given. Finally, some conclusions and comments are made in the last section.

Chapter 2

Network Model

This is a description of the interference-based model of a radio network, represented by a set of nodes $\mathcal{V}$ and the basic path-loss $L_{\text{b}}(i,j)$ between any two distinct nodes (v_i, v_j), $i \neq j$.

In the following we will assume isotropic antennas and that all nodes use equal transmission power. This is mainly for simplicity, but in section 6 we present a short discussion of the consequences of directional antennas and varying transmission power.

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

$$\Gamma_{ij} = \frac{P_i}{L_{\text{b}}(i,j)\, N_{\text{r}}}, \tag{2.1}$$

where P_i denotes the power of the transmitting node v_i, $L_{\text{b}}(i,j)$ is the basic transmission path-loss between nodes v_i and v_j, and N_{r} is the total noise power in the receiver. For convenience, we define $\Gamma_{ii} = 0$ corresponding to the physical situations of a node not being able to transmit to itself.

We say that a pair of nodes (v_i, v_j) form a *link* (i,j), if the signal-to-noise ratio (SNR) is not less than a threshold, γ_0. That is, the set of links in the network, $\mathcal{K}$, is defined:

$$\mathcal{K} = \{(i,j) : \Gamma_{ij} \geq \gamma_0\} \ . \tag{2.2}$$

For a set of links, $K \subseteq \mathcal{K}$, we define the *transmitting nodes*:

$$V_{\text{T}}(K) = \{v_i : (i,j) \in K\} \ .$$

For any link, $(i, j) \in K$, we define the *interference* as

$$I_K(i,j) = \sum_{v_k \in V_T(K) \setminus v_i} \frac{P_k}{L_b(k,j)}. \tag{2.3}$$

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

$$\Pi_K(i,j) = \frac{P_i}{L_b(i,j)(N_r + I_K(i,j))}. \tag{2.4}$$

We assume that any two radio units can communicate a packet without error if the SIR is not less than a threshold, γ_1. 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 nodes or links assigned time slot t. A schedule is called conflict-free if the SIR is not less than the threshold γ_1 for all receiving nodes in all sets X_t.

Furthermore, we 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.

Chapter 3

Node and Link Assignment

In a *node assigned* schedule, a node is allowed to transmit to any of its neighbors in its slot. If the schedule is to be conflict-free this means that we have to guarantee that we will not have a conflict in any of the neighboring nodes. In link-oriented assignment, the directed link is assigned a slot. A node can then only use this slot or transmission to a specific neighbor. In general this knowledge can be used to achieve a higher degree of spatial reuse. The effect is higher throughput.

In the following, we first describe the criteria required for a set of links to be able to transmit simultaneously with sufficiently low interference level at the receiving nodes. Then, we do the same for a set of nodes.

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. We 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. Alternatively, we say that a set of links K and the set of its adjacent links $\Psi(K)$ must be disjoint:

$$K \cap \Psi(K) = \emptyset. \tag{3.1}$$

The signal-to-interference criteria (2.4) give the following condition

$$\Pi_K(i, j) \geq \gamma_1 \;\; \forall \;\; (i, j) \in K. \tag{3.2}$$

If the two conditions above, (3.1) and (3.2), hold for a set of links $K \in \mathcal{K}$, we say that the links in K can *transmit simultaneously*.

Similarly we will state two necessary conditions for the situation when all the nodes in a set V are allowed to transmit packages simultaneously. Let the *neighbors* $\Omega(v)$ to a node $v \in V$ be the set of all nodes that have a link from v to itself. The neighbors are the nodes that v can possibly transmit a packet to. Similarly, let $\Omega(V)$ denote the union of all neighbors of all nodes in V.

The *first condition* is that two neighbors cannot transmit at the same time. Another way to say this is that the sets V and $\Omega(V)$ must be disjoint:

$$V \cap \Omega(V) = \emptyset. \tag{3.3}$$

Let $K(V)$ be the set of all links from the nodes in V to their neighbors in $\Omega(V)$. Since it must be possible to use all the links in $K(V)$ for transmission simultaneously, we state the *second condition:*

$$\Pi_{K(V)}(i,j) \geq \gamma_1 \text{ for all } (i,j) \in K(V)\,. \tag{3.4}$$

If the above two conditions, (3.3) and (3.4), hold for a set of nodes $V \in \mathcal{V}$, we say that the set of nodes can *transmit simultaneously.*

Chapter 4

Extended Transmission Rights

Notice that the interference term in (2.3) only depends on which nodes are transmitting and not on the nodes that are receiving messages. Assume that a node is assigned as a transmitter in a slot, i.e. an outgoing link of the node is assigned the slot. If this node redirects the transmission to a node other than the assigned receiving node, the inequality in (3.2) still holds for all links originally assigned to the slot. This means that the interference level of the other simultaneously receiving nodes will not change. (Recall the assumption of omni-directional antennas.) The redirected transmission in itself cannot of course always be guaranteed to be conflict-free.

Based on these observations we suggest the following scheme for extending transmission rights for any given link assigned schedule. When a link is assigned a time slot, the node first checks whether there is a message to transmit on that link. If there is no such message, any other link with the same transmitting node may be used if the node has a message to transmit. Preferably, links that are conflict-free should have priority in order to avoid unnecessary packet loss.

We call this strategy Link assignment with Extended Transmission rights (LET).

To illustrate how this scheme works, we provide a small example. Assume links 1,2, and 3 in figure 4.1 have been scheduled to transmit in the same slot. Let us study node A in more detail. If node A does not have any messages to transmit to B, it is permitted to transmit on one of the links 4 or 5 in the slot assigned to link 1. Now, if both links 2 and 3 are used (or these nodes also use LET) neither transmission on 4 or 5 will be successful. However, for low traffic

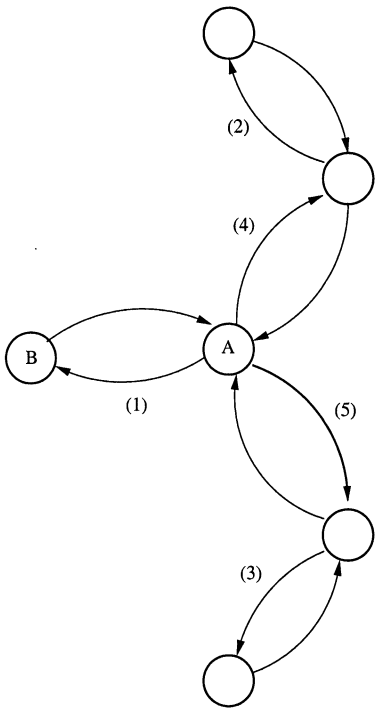

Figure 4.1: A small example.

the probability that this would happen is small. If none of the other two nodes use their slot, the redirected transmission will be successful. If only one of them transmits we still have 50 percent probability of success. This is because node A cannot know which (if any) of the others will transmit.

We now continue by proving that by redirecting the transmissions the nodes in the network will not cause any conflict at any node which has not redirected their transmission. Assume that K is a set of links such that they can transmit simultaneously according to equations 3.1 and 3.2, i.e.

$$\Pi_K(i,j) \geq \gamma_1 \ \forall \ (i,j) \in K.$$

Furthermore, assume that the transmitting nodes of $K_{\mathrm{R}} \subseteq K$ redirects their transmissions to other receiving nodes than scheduled in the initial link schedule and that K_{NR} is the rest of the links, i.e.

$$K_{\mathrm{NR}} = K \setminus K_{\mathrm{R}}.$$

Let K_{U} be the set of links used by the redirecting nodes. Therefore,

$$V_{\mathrm{T}}(K_{\mathrm{U}}) = V_{\mathrm{T}}(K_{\mathrm{R}}).$$

If K_{NR} is to be conflict-free, the following inequality must be valid

$$\Pi_{K_{\mathrm{NR}} \cup K_{\mathrm{U}}}(i,j) \geq \gamma_1 \;\; \forall \;\; (i,j) \in K_{\mathrm{NR}}.$$

For any $(i,j) \in K_{\mathrm{NR}}$, we can write

$$\Pi_{K_{\mathrm{NR}} \cup K_{\mathrm{U}}}(i,j) = \frac{P_i}{L_{\mathrm{b}}(i,j)(N_{\mathrm{r}} + I_{K_{\mathrm{NR}} \cup K_{\mathrm{U}}}(i,j))}.$$

and

$$I_{K_{\mathrm{NR}} \cup K_{\mathrm{U}}}(i,j) = \sum_{v_k \in V_{\mathrm{T}}(K_{\mathrm{NR}} \cup K_{\mathrm{U}}) \setminus v_i} \frac{P_k}{L_{\mathrm{b}}(k,j)}.$$

However,

$$V_{\mathrm{T}}(K_{\mathrm{NR}} \cup K_{\mathrm{U}}) = V_{\mathrm{T}}(K_{\mathrm{NR}}) \cup V_{\mathrm{T}}(K_{\mathrm{U}}) = V_{\mathrm{T}}(K_{\mathrm{NR}}) \cup V_{\mathrm{T}}(K_{\mathrm{R}}) = V_{\mathrm{T}}(K),$$

resulting in, $I_{K_{\mathrm{NR}} \cup K_{\mathrm{U}}}(i,j) = I_K(i,j)$ and $\Pi_{K_{\mathrm{NR}} \cup K_{\mathrm{U}}}(i,j) = \Pi_K(i,j)$, which of course fulfills 3.2.

Chapter 5

Evaluation Parameters

The first parameter we evaluate is the average end-to-end packet delay D. *Packet delay* is the time, in time slots, from the arrival of a packet at the buffer of the arrival node v_k to the arrival of the packet at the destination node v_l.

This parameter has been estimated using simulations.

The relaying of traffic in multi-hop networks causes a considerable variation of the traffic load on the links and nodes in a network. To achieve large capacities, efficient traffic-controlled schedules have to compensate for this problem.

In a traffic-controlled schedule, links or nodes can use several slots, see [17], according to the traffic load. We define h_{ij} as the number of slots allocated to link (i, j) within a frame in a schedule. The corresponding notation for node assignment is h_i.

Note that the problem with varying traffic loads may be less severe in a node-assigned schedule, since the variation of traffic is averaged over a node.

In our traffic model we assume point-to-point traffic, i.e. a packet entering the network has only one destination. Packets enter the network at *entry nodes* according to a probability function, $p(v), v \in V$, and packets exit the network at *exit nodes*. When a packet enters the network, it has a destination, i.e., an exit node from the network. The destination of a packet is modeled as a conditional probability function, $q(w|v), (w, v) \in V \times V$, i.e. given that a packet has entry node v, the probability that the packet's destination is w is $q(w|v)$. For simplicity we will assume a uniform traffic model, i.e. $p(v) = 1/N$, and $q(w|v) = 1/(N-1)$, where N is the number of nodes, $N = |V|$. This assumption will not affect our results since we use traffic-controlled schedules, thereby compensating for variations caused by the input traffic model.

Let λ be the total traffic load of the network, i.e. the average number of packets per time slot arriving at the network as a whole. Then, $\lambda/N(N-1)$ is the total average of traffic load entering the network in node v_i with destination node v_j. As the network is not necessarily fully connected, some packets must be relayed by other nodes. In such a case, the traffic load on each link cannot be calculated until when the traffic has been routed.

Now, let R denote the routing table where the list entry $R(v,w)$ at v,w is a path from entry node v to exit node w. Let the number of paths in R containing the *directed* link (i,j) be equal to Λ_{ij}.

Further, let λ_{ij} be the average traffic load on link (i,j). Then λ_{ij} is given by:

$$\lambda_{ij} = \frac{\lambda}{N(N-1)}\Lambda_{ij}.$$

For node assignment, we have, λ_i as the average traffic load on node v_i. Where λ_i is given by

$$\lambda_i = \frac{\lambda}{N(N-1)} \sum_{j:(i,j)\in K} \Lambda_{ij} = \frac{\lambda}{N(N-1)}\Lambda_i,$$

and where Λ_{ij} and Λ_i are the relative traffic of a link and a node, respectively.

The maximum traffic load giving bounded packet delay is commonly referred to as the throughput of the network. We define the throughput as the number λ^* for which the following expressions hold for all traffic loads λ

$$\begin{cases} \lambda < \lambda^* & \text{yields bounded delay} D \\ \lambda > \lambda^* & \text{yields unbounded delay} D \end{cases}$$

It is difficult to find a schedule achieving maximum throughput of all schedules, but an efficient way to achieve high throughput is by fully compensating the schedule for the traffic loads on the links. This means that each link receives a number of time slots in direct proportion to the traffic flowing over it. If a link A has five times as much traffic as a link B, it should also have five times as many time slots. One way of making a schedule fully compensated for traffic under the assumption of uniform traffic is to set $h_{ij} = \Lambda_{ij}$.

Chapter 6

Basic Properties

Figure 6.1 shows the average packet delay for different input traffic loads λ for a node assigned, link assigned and a link assigned schedule using extended transmission rights schedule for a network of 30 nodes.

We see from this figure that in this network link assignment is preferable to node assignment for high traffic loads. For low traffic loads node assignment achieves a smaller delay. The LET method combines the advantages of the two methods and in this case achieves a smaller delay for all traffic loads.

In this figure some areas of interest can be seen. The STDMA curves are rather flat until the traffic load approaches the maximum throughput, when it rises steeply. In this example, this is especially the case for LET. Therefore, it is sufficient if we concentrate on the delay at very low traffic loads and the maximum throughput.

At low traffic loads, we will study the relation between the delay of node assignment, the delay of link assignment, and the delay of LET.

At high traffic loads, the relation between throughput of node assignment and link assignment is interesting. The relation between the throughput of LET and link assignment is also interesting, but at very high traffic levels most of the links in the network will have messages in queue. For this case, LET will appear mainly as link assignment and achieve the same throughput as the link-assigned schedule it is based on, if the link-assigned schedule is fully traffic compensated.

This is because at very high traffic loads the probability that a link will have a message to transmit in its time slot will be close to one. The LET property will not be used, and the network will appear exactly as a link-assigned schedule. No conflicts will appear, resulting in the same throughput as the link-assigned

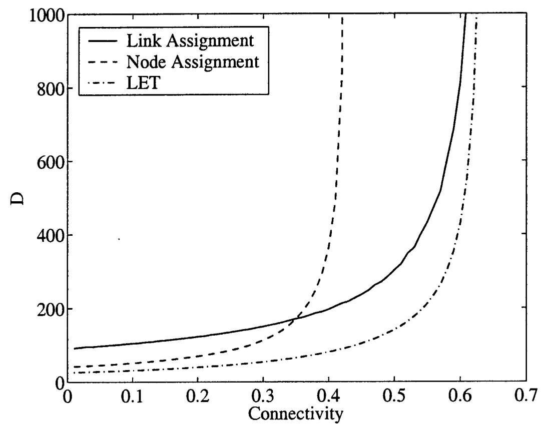

Figure 6.1: Average packet delay in a 30-node network.

schedule.

If the link-assigned schedule is not fully compensated for varying network traffic, LET will give at least as high throughput as the link-assigned schedule. This is because no packet transmitted on a link assigned to the time slot is lost in LET, and a highly loaded link can use one of the lower loaded outgoing links from that node.

Although any link-assigned schedule may be used to extend transmission rights, some link schedules may give LET more or less desirable properties. We discuss what effect the link schedule has on delay.

At low traffic load, the nodes will normally only have at most one message at a time. In this case LET behaves as node-assignment, with the node-assigned schedule as the transmitting nodes in the link-assigned schedule. A problem when generating STDMA schedules appear when to determine which slots to give a node that is going to receive more than one slot, since delay through the node depends on which specific time slots the node is given.

For example, if a node has received two time slots and these are spread in such a way that the distance between them is approximately half the frame length, then for low traffic loads the delay will be at most half the frame length. However, if the node is given two consecutive time slots, the maximum delay might be the entire frame length. That is, it is usually efficient to spread a node's time slots evenly over the frame. This problem gets worse if nodes receive many time slots, especially since a large part of the traffic usually flows through these nodes.

In some algorithms, see e.g., [15], the time slots a node or link is given is attempted to be spreaded equally over the frame. However, even if the link schedule has perfectly spread time slots, this may not be the case for the transmitting nodes. Therefore, LET might give considerably higher delay than a node-assigned schedule if the link schedule tends to give the transmitting nodes consecutive time slots.

Any assignment algorithm, especially if it is of a greedy type, has a set of rules to determine which link to assign to a time slot. One method used is node ID, i.e. the lower the ID number, the higher the priority. To assign links, the pair of node IDs of the transmitting and receiving nodes can be used. A sorted list according to link priority would then give the outgoing links from a node consecutive places in the list. Even if another system for link priority is used, node ID is eventually used if priority is equal for several links.

Now, assume we have a fully connected network, i.e. all nodes can communicate with all other nodes without relaying. Furthermore, in this case we can assume that there is no spatial reuse, although in a link schedule, when using an interference-based model, this might be possible due to capture effects. In this case, the assigned schedule would be the sorted list described above, which gives high packet delay.

One way to avoid this problem is to give the links a link ID which is random, although different for each link.

The assumptions used in this paper is the use of omnidirectional antennas and equal transmission power of all nodes in the network. If this is not the case, a node cannot redirect its transmission to any other of its neighbors since this might require an increase of signal power or redirection of the antennas. Any change of the outgoing power strength and direction can ruin the conflict-free properties of the other receiving nodes.

However, some of the nodes may still be reached without such a change and the LET properties can still be used with these nodes, although this is less efficient than if all nodes could be reached.

Chapter 7

Analyses

In this section we will give some analytical results that are useful when evaluating the properties of LET. We first discuss throughput and then continue with an approximation of the packet delay at low traffic arrival rate.

In [18], the throughput in a network with fixed capacities on the links and fixed routing is determined. In [19], this is specifically done for a link-assigned schedule and a node-assigned schedule using the same notation as in this paper. The maximum throughput for the link assigned schedules can be written as

$$\lambda_{\mathrm{L}}^{*} = \min_{(i,j)} \frac{N(N-1)h_{ij}}{T_{\mathrm{L}}\Lambda_{ij}}, \tag{7.1}$$

where T_{L} is the length of the link-assigned schedule.

The corresponding result for node assignment can be written as:

$$\lambda_{\mathrm{N}}^{*} = \min_{(i)} \frac{N(N-1)h_{i}}{T_{\mathrm{N}}\Lambda_{i}}, \tag{7.2}$$

where T_{N} is the length of the node-assigned schedule.

These formulas can easily be motivated by noticing that the average packet delay will be infinite if any of the links/nodes in the network are saturated, assuming there is no rerouting of traffic. The throughput is then the smallest value of λ such that the input traffic to any link $\Lambda_{ij}\lambda/N(N-1)$ equals the capacity of the link T/h_{ij}.

Furthermore, if we use schedules that are fully compensated for traffic, i.e. $h_{ij} = \Lambda_{ij}$ the formula for link assignment can be simplified to

$$\lambda_{\mathrm{L}}^{*} = \frac{N(N-1)}{T_{\mathrm{L}}}, \tag{7.3}$$

and, similarly, for node assignment

$$\lambda_{\mathrm{N}}^* = \frac{N(N-1)}{T_{\mathrm{N}}}. \tag{7.4}$$

The fraction between throughput of a link-assigned schedule and the throughput of a node assigned schedule can then be written as:

$$\frac{\lambda_{\mathrm{L}}^*}{\lambda_{\mathrm{N}}^*} = \frac{T_{\mathrm{L}}}{T_{\mathrm{N}}}. \tag{7.5}$$

We now derive an expression for the average packet delay.

$$D_{\mathrm{L}} = \sum_{(i,j)\in K} \frac{\Lambda_{ij}}{N(N-1)} d_{ij}, \tag{7.6}$$

where d_{ij} is the delay on link(i,j).

In order to determine the packet delay we make two extra assumptions. Even if they are not fulfilled, it is still a useful approximation of the packet delay.

First, in the schedules, the slots assigned to a node are perfectly spread over the frame, i.e. the distance between two assigned slots is equal. The algorithm used in the simulations attempts to do this, but the algorithm is not optimal, and it is not always possible to spread the slots evenly.

Second, the relay traffic can be described as a Poisson process. This is certainly not the case, since relay packets can only arrive in specific time slots. However, it is normally a good approximation. This is an attempt to use the same principle as the independence assumption [18], but for a TDMA network.

With these assumptions, the delay through a link can at low traffic arrival rate be written as:

$$d_{ij} = \frac{T_{\mathrm{L}}}{2h_{ij}},$$

which inserted in (7.6) gives the average packet delay of a link-assigned schedule

$$D_{\mathrm{L}} = \sum_{(i,j)\in K} \frac{\Lambda_{ij}}{N(N-1)} \frac{T_{\mathrm{L}}}{2h_{ij}}.$$

Furthermore, if the schedule is fully compensated for traffic, we have

$$D_{\mathrm{L}} = \frac{MT_{\mathrm{L}}}{2N(N-1)},$$

where M is the number of directed links in the network.

The corresponding result for a node-assigned schedule is

$$D_{\mathrm{N}} = \sum_{i \in V} \frac{\Lambda_i}{N(N-1)} \frac{T_{\mathrm{N}}}{2h_i},$$

and for a schedule fully compensated for traffic

$$D_{\mathrm{N}} = \frac{NT_{\mathrm{N}}}{2N(N-1)}.$$

The relation between the delay of link assignment and the delay of node assignment can then be written as:

$$\frac{D_{\mathrm{L}}}{D_{\mathrm{N}}} = \frac{M}{N}\frac{T_{\mathrm{L}}}{T_{\mathrm{N}}} = \frac{M}{N}\frac{\lambda_{\mathrm{N}}^*}{\lambda_{\mathrm{L}}^*}. \tag{7.7}$$

Simulations in section 8 will indeed show that this is a good approximation except for low connectivity.

The same assumptions as above can be made for LET as well. But, since LET behaves like a node-assigned schedule at low traffic loads, the link-assigned schedule would have to try to spread the nodes, corresponding to the links in the schedule, evenly over the frame instead of the links. However, the algorithm used in the simulations does not attempt to do this. This results in a larger discrepancy than for node assignment or link assignment when comparison with simulations is made.

The delay using LET under these assumptions can be written as:

$$D_{\mathrm{LET}} = \sum_{i \in V} \frac{\Lambda_i}{N(N-1)} \frac{T_{\mathrm{L}}}{2h_i},$$

and for a schedule fully compensated for traffic

$$D_{\mathrm{LET}} = \frac{NT_{\mathrm{L}}}{2N(N-1)}.$$

The relation between delay of link assignment and delay of LET can be written as

$$\frac{D_{\mathrm{L}}}{D_{\mathrm{LET}}} = \frac{M}{N} \tag{7.8}$$

and the relation between delay of node assignment and delay of LET can be written as

$$\frac{D_{\mathrm{N}}}{D_{\mathrm{LET}}} = \frac{T_{\mathrm{N}}}{T_{\mathrm{L}}} = \frac{\lambda^*_{\mathrm{L}}}{\lambda^*_{\mathrm{N}}}. \tag{7.9}$$

As simulations in section 8 show, these last two approximations work less well than equation 7.7, due to the less efficient spreading of time slots.

Chapter 8

Numerical Evaluation

We evaluate delay and throughput for simulated networks of different connectivity and number of users.

In the comparisons, 500 networks of size 10, 20, and 40 nodes have been generated with different connectivity. The connectivity is varied by changing the transmission power, P, for a network. All networks are connected, i.e. there is always a path between any pair of nodes. We define connectivity as the fraction of nodes in the network that can be reached by a node, in one hop, on average, 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 to calculate the basic transmission path-loss, see [20] for more details.

The algorithms we use for generating the link and node-assigned schedules for the simulations are fully traffic compensated. The link-assignment algorithm is described in [15], where $h_{ij} = \Lambda_{ij}$, and the node-assigned algorithm is described in [21]. The only difference between these algorithms is the assignment part.

The algorithm used is a greedy algorithm that assigns slots according to priority. The priority of a link/node is the traffic load through a node/link multiplied by the time since it was last assigned a time slot.

In short, the algorithm works as follows: Choose the node/link with highest priority which has not yet been checked in the time slot. Assign it to the time slot if possible. If all nodes/links with time slots left have been checked, continue to the next slot. Proceed until all nodes/links have been scheduled their guaranteed time slots.

The link ID is random as described in section 6.

For each of the generated networks, average delay has been determined by using simulations. In the simulations, these additional assumptions have been made:

Shortest route, i.e. packets sent between two nodes will always use the path which requires the least number of transmissions. If several routes of the same length exist, all packets between two specific nodes will always use the same route. When estimating packet delay, packets are generated by a pseudo-Poisson process with intensity λ and with a uniform traffic distribution. We have chosen Poisson traffic for simplicity and because we want to compare the simulation results with the approximations in section 7.

When we are using node or link assignment, all packets are assumed to be perfectly received, and no retransmissions are considered. For LET, a perfect feedback channel with no delay is assumed. This of course is not very realistic, but the effect is small for very low traffic levels when no collisions occur and for very high traffic levels when the LET property has no effect. Since high traffic and low traffic are the interesting areas in this investigation, the effect of this assumption is only a simplification of the simulations. In a realistic scenario, more complex acknowledgment schemes should be used since STDMA assumes safe transfer of packets over the links.

We start the investigation by studying networks with high traffic loads. The first parameter we study here is the ratio between maximum throughput λ_{L}^* of link assignment and maximum throughput λ_{N}^* of node assignment, i.e.

$$\lambda_{\mathrm{L}}^*/\lambda_{\mathrm{N}}^*,$$

which we know from equation (7.5) equals $T_{\mathrm{N}}/T_{\mathrm{L}}$.

As can be seen in figure 8.1, this ratio exhibits considerable variations over the networks studied. One conclusion in these simulations is that link assignment provides higher throughput. This is not so surprising since the degree of spatial reuse is higher for link assignment.

To determine how much better link assignment can be, we plot, in figure 8.2, the ratio $\lambda_{\mathrm{L}}^*/\lambda_{\mathrm{N}}^*$ averaged over connectivity for networks of different sizes. As can be seen, $\lambda_{\mathrm{L}}^*/\lambda_{\mathrm{N}}^*$ increases with the size of the network and decreases if connectivity is increased.

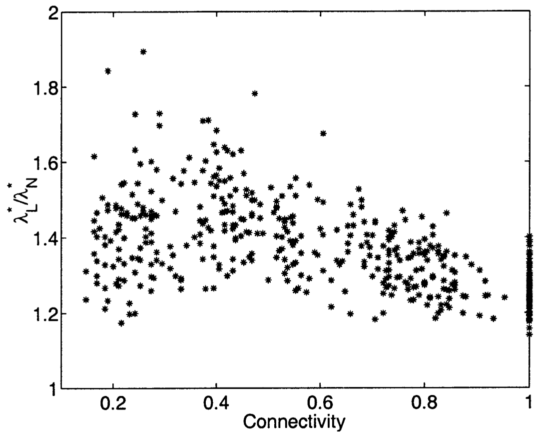

Figure 8.1: The figure shows the ratio between maximum throughput for link assignment and node assignment for networks of different connectivity. The relation is plotted for 500 networks of size 20 nodes.

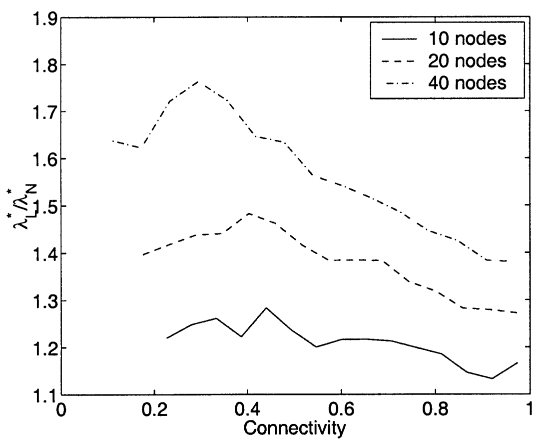

Figure 8.2: The figure shows the average ratio between maximum throughput for link assignment and node assignment for networks of different connectivity. Ratio between throughput for networks of different size 10, 20, and 40 nodes.

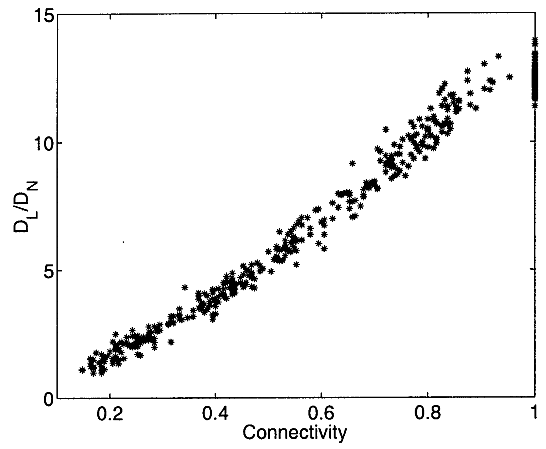

Figure 8.3: The figure shows the ratio between average packet delay for link assignment and average packet delay for node assignment versus degree of connectivity. The ratio is plotted for 500 networks of size 20 nodes.

We continue by studying the average delay at low traffic loads.

The second parameter studied is the ratio between packet delay of link assignment D_{L} and node assignment D_{N} at low traffic loads. In figure 8.3 this parameter can be studied. The variance is rather low, and a linear relationship between this ratio and connectivity can be detected.

To see how well equation 7.7 approximates the delay, we plot $D_{\mathrm{L}}/D_{\mathrm{N}} * \lambda_{\mathrm{N}}/\lambda_{\mathrm{L}}$, which should be approximately M/N. As can be seen in figure 8.4, this works fairly well; $D_{\mathrm{L}}/D_{\mathrm{N}}$ is slightly lower than predicted, independent of connectivity.

The next comparison is node assignment and LET. Therefore, the second parameter studied is the ratio between packet delay of node assignment and LET at low traffic loads, i.e.

$$D_{\mathrm{N}}/D_{\mathrm{LET}}.$$

If this parameter is greater than one, LET is always preferable, and if it is less than one, node assignment is preferable for low traffic loads.

In figure 8.5, this parameter is shown for networks of 20 nodes. As can be seen, there are some variations over the different networks. In figure 8.6, we plot the ratio $D_{\mathrm{N}}/D_{\mathrm{LET}}$ averaged over connectivity for networks of different sizes.

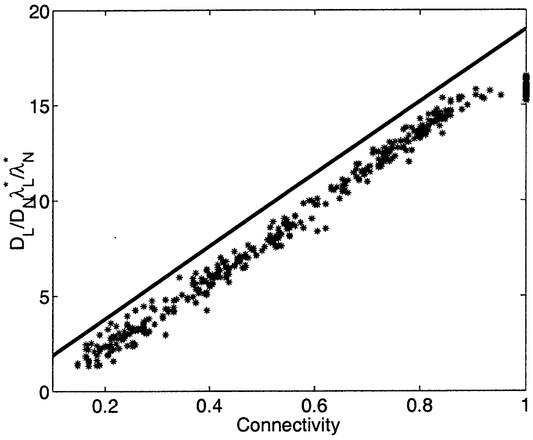

Figure 8.4: The figure shows the ratio between average packet delay for link assignment and average packet delay for node assignment multiplied with the ratio between the throughput for link assignment and throughput for node assignment. This should approximately be equal to the connectivity of the network multiplied with $N - 1$ which is the line also plotted in the figure. This is plotted for 500 networks of size 20 nodes.

As can be seen, $D_{\text{N}}/D_{\text{LET}}$ decreases with the connectivity. This is because the gain in spatial reuse of link assignment compared with node assignment decreases with connectivity. Its increase with network size is consistent with the approximation in equation 7.9 since it should be close to $\lambda_{\text{L}}/\lambda_{\text{N}}$. To more closely see how well the approximation works, we plot in figure 8.7 $D_{\text{LET}}/D_{\text{N}} * \lambda_{\text{L}}/\lambda_{\text{N}}$, which should give results close to one for all connectivities.

As can be seen, the approximation works well for low to medium connectivity. The error is greatest for high connectivity. These results seem independent of network size, because the problem of spreading the time slots over the frame increases with connectivity.

It can be concluded that for the chosen assignment algorithms, except for high connectivity, a link-assigned schedule with extended transmission rights gives lower delay than a node-assigned schedule. For very high connectivity, LET can give a higher delay than node assignment. This is because the link-assigned schedule our method is based on does not attempt to spread the time slots a node is assigned evenly over the frame.

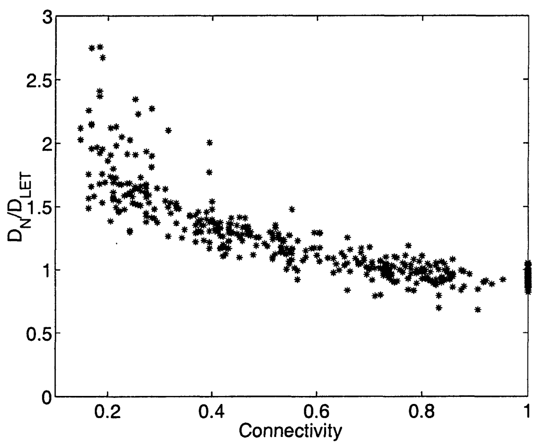

Figure 8.5: The figure shows the ratio between the delay of node assignment and the delay of LET. This is plotted for 500 networks of size 20 nodes.

We conclude the study of average packet delay by examining the relation between packet delay of link assignment and packet delay of LET at low traffic loads. In figure 8.8, simulation results of this parameter can be studied for networks of 20 nodes.

As can be seen, this parameter exhibits some variation over the simulated networks. Included in the figure is also the approximated delay according to equation 7.8. The accuracy of the approximation decreases with an increase of network connectivity. This is probably due to badly spreaded time slots described in section 6.

In figure 8.9, this relation is averaged for networks of different sizes. It can be concluded that LET decreases the average delay considerably compared to link assignment. This effect increases with network size and connectivity. This is not a surprising result, since increasing network size or connectivity increases the number of outgoing links of a network node, thereby giving LET more opportunities.

From these simulations and the knowledge that LET always achieves at least as high throughput as link assignment, we can see that LET is preferable to both link and node assignment except for networks of very high connectivity and low traffic.

However, there might be situations where LET is not applicable, e.g. one-

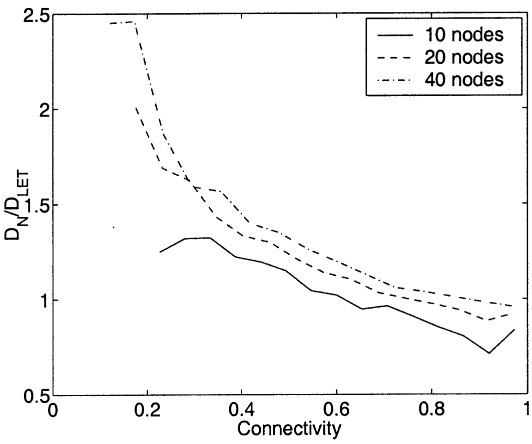

Figure 8.6: The figure shows the average ratio between delay for node assignment and delay for LET for networks of different connectivity. Ratio between delay for networks of different size 10, 20, and 40 nodes.

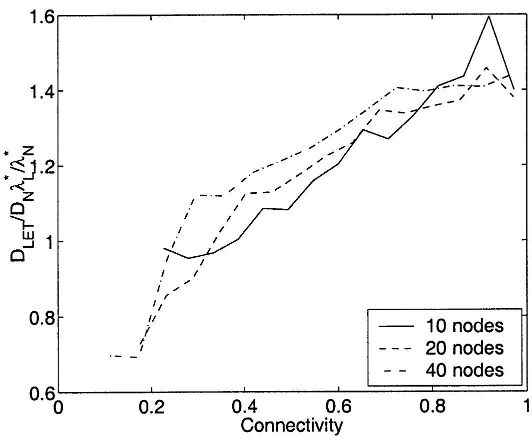

Figure 8.7: The figure shows the ratio between the delay of LET and the delay of node assignment multiplied with the ratio between the throughput for link assignment and node assignment. This should be approximatly equal to one for all network connectivities. This is plotted for networks of different connectivity for networks of different size 10, 20, and 40 nodes.

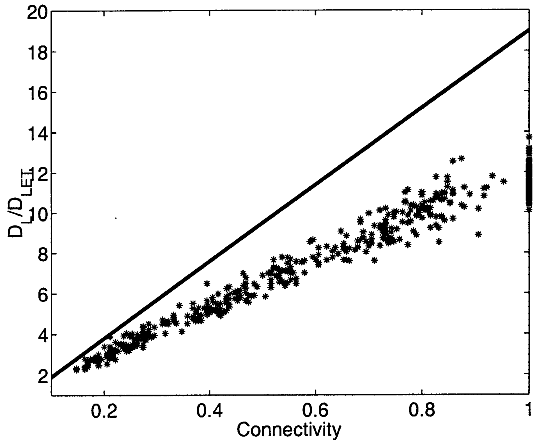

Figure 8.8: The figure shows the ratio between the delay of link assignment and the delay of LET. This is plotted for 500 networks of size 20 nodes. This should approximately be equal to the connectivity of the network multiplied with $N-1$ which is the line also plotted in the figure.

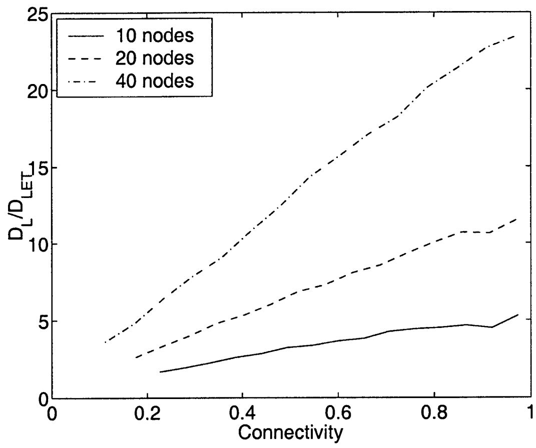

Figure 8.9: The figure shows the average ratio between delay for link assignment and delay for LET for networks of different connectivity. This ratio is plotted for networks of size 10, 20, and 40 nodes.

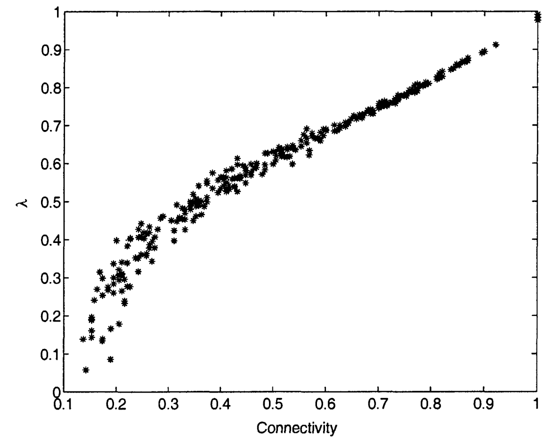

Figure 8.10: The figure shows the input traffic level giving equal packet delay for different network connectivity. This is plotted for 500 networks of size 20 nodes.

way communication links. So we will also study the input traffic load of the network which gives equal packet delay for node and link assignment. This parameter is interesting since it determines for what traffic loads link/node assignment is preferable. That is, for traffic loads higher than this parameter, link assignment is preferable; at lower traffic loads, node assignment is preferable.

As can be seen in figure 8.10, the variance over the simulated networks of this parameter is less than for the other parameters, which means that the average value is highly interesting. This average is shown in figure 8.11. As can be seen, this average is rather independant of the network size. A small increase with the network size can seen, at least for low connectivity. This means that we can determine the preferred assignment method of node and link assignment by studying these average values. If we are above, link assignment is preferrable; below, node assignement. This can be done with knowledge of connectivity and input traffic to the network.

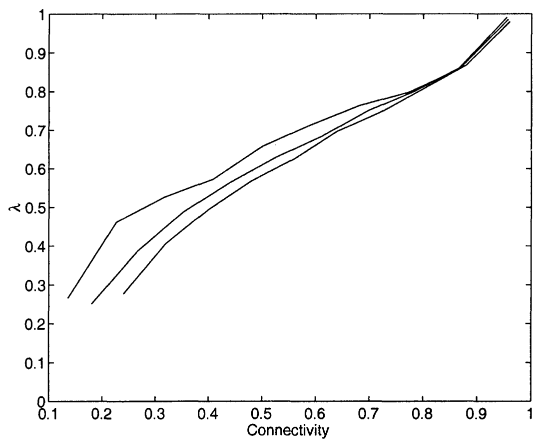

Figure 8.11: The traffic load which gives equal delay for 400 networks of sizes 10, 20, and 60 nodes. 10 nodes at the bottom and 60 nodes at the top.

Chapter 9

Conclusions and Comments

The preferable assignment method of link and node assignment can be determined with knowledge only of the connectivity of, and input traffic to, the network.

For high traffic loads, link assignment is better than node assignment due to higher reuse efficiency. However, for low traffic loads, node assignment is preferable due to lower average time between transmissions.

Furthermore, the intersection point, i.e. the traffic load λ_I when both methods achieve the same delay, increases with increasing connectivity of the network, according to figure 8.11. For traffic loads above this intersection, link assignment is preferable, whereas for traffic loads below this intersection, node assignment is preferable.

According to our simulations, LET gives, for our choice of algorithm, much lower delay than link assignment, while it achieves at least as high throughput. Furthermore, LET gives lower delay than node assignment for networks of low and medium connectivity. This indicates that LET can give considerable improvements to existing schedules.

These results hold for unicast traffic. For broadcast and multicast traffic, node assignment strategies have obvious advantages. This points toward a different result in such cases.

It should be noticed that LET might cause higher power consumption than link assignment since all neighboring nodes have to receive the message. It can also cause somewhat higher power consumption than node assignment since we may have conflicts, and some packet may have to be retransmitted.

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