An Analysis of Bluetooth Scatternet Topologies

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Abstract: Bluetooth "scatternets" are targeting wider geographical area applications in factories, warehouses, shopping malls and various sensor network applications. Though some earlier work has looked at scatternet formation and scheduling issues, less attention has been given to optimizing scatternet topologies. We consider in this paper topological design of scatternets, taking into consideration application traffic requirements. We study appropriate topologies, and size the network in terms of piconets. We develop a scatternet queuing model and use it to compare the delay-throughput characteristics of various topologies. We find that the best topology is application dependent. The analytical model is also used to determine the optimal point to operate a scatternet, i.e., the traffic load that saturates the network. We validate all our analytical results by simulations.

1. Introduction

Bluetooth [1] piconets may be inter-connected to form larger networks called scatternets that enhances its networking capabilities. The low cost and likely large diffusion of Bluetooth devices is likely to bring down its cost and enable Bluetooth-enabled devices to be used in a wide array of applications in various scatternet architectures.

In general, there will be two distinct modes in which Bluetooth-based scatternets will be used [2]. One will be in dynamic environments, such as a conference, where an on-the-fly formed scatternet will allow Bluetooth-enabled users to share information such as visiting cards, multimedia files etc. The second mode of use of scatternets will be in static environments in which they will be configured similar to wired networks. An example of a static mode is a network connecting household appliances. Another example is a shopping mall, in which a scatternet covering the whole mall may direct the client towards the products he is interested in, or advise him about "special offers." Static deployments also incorporate many sensor network scenarios [13]. For example, a scatternet of sensor-enabled Bluetooth devices may be deployed in a warehouse to provide inventory tracking, i.e., locating items, reporting on need to restock [3]. This paper focuses on these kinds of static environments.

Scatternet architectures have received attention in the literature recently. The scheduling of gateways among piconets has been addressed in [4] [5]. Scatternet formation has been addressed in [6] [7] [12], but the environments dealt with are typically dynamic where nodes enter and leave the network throughout its lifetime.

In [7], the authors suggest that it is desirable to minimize the number of piconets, since a large number of piconets will incur more collisions. On the other hand, each added piconet would increase system capacity. Another issue is the optimal number of gateways to be used in connecting piconets. In this paper, we present an analytic approach for designing a scatternet. We evaluate analytically the impact of the number of piconets and the number of gateways on the performance of a scatternet under specific application traffic patterns. The analytic model estimates correctly the delays in a scatternet given an end-to-end traffic load. We further show how the model is used to identify desirable characteristics of scatternets, and compare different scatternet structures.

In Section 2, we discuss the Bluetooth technology. In Section 3, we develop the queuing model and in Section 4, we present performance results for various scatternet topologies considering two application traffic patterns. Section 5 presents concluding remarks and suggestions for potential future work.

2. Bluetooth

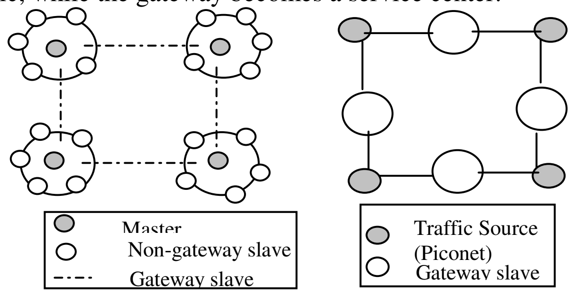
Bluetooth piconets can be interconnected to form a scatternet. This requires units, called gateways, to belong to more than one piconet on a time-division multiplexing basis. The concept of Rendezvous Points (RPs) and Rendezvous Windows (RWs) has been introduced in [4]. By defining RPs and RWs appropriately, it is possible to define a scheduling scheme in which the gateway gets a certain fraction of bandwidth in each of its piconets. We further specify the scheduling assumed in our models in Section 4.

The Bluetooth model used for the simulation experiments in this paper is built on NS-2 [8]. The model implements the standard features of Bluetooth like Frequency Hopping, Multi-Slot Packets, and Fast ARQ (Automatic Retransmission Query). In addition, it also has support for defining scatternets, and gateway scheduling algorithms.

3. Queuing Analysis

In this section, we present an analytical model for studying delay-throughput properties in Bluetooth networks. We first present a queuing model for a gateway and then perform the analysis by treating a Bluetooth network as a *network of queues, where each queue represents a gateway.*

We focus on gateways and model them as service centers in a network of queues, with "external traffic" fed into the network by masters and non-gateway slaves. For example, a Bluetooth network and its equivalent model are shown in Fig. 1. Note that the piconet in Fig 1 (b) only serves as a source of traffic, while the gateway becomes a service center.



(a) (b)

Fig 1: A Bluetooth network (a) and the corresponding network of service centers model (b).

3.1 Queueing Model of a Gateway

To develop the queueing model for a gateway, we use the following observations regarding a gateway's behaviour:

(i) The *service rate* of a gateway depends upon the polling it gets in each piconet it belongs to. Thus, if a gateway gets a fraction x of the polling in a piconet, its service rate for the piconet is (BW*x), where BW is the Bluetooth bandwidth. Also, if a gateway belonging to two piconets gets the same fraction of polling x in each piconet, it may be seen as a link between the two piconets with a bandwidth equal to (BW*x). In other words, it will behave as a service center with a service rate of (BW*x). (We assume here and in the rest of the paper that a gateway can belong to a maximum of 2 piconets; our analysis does not address the behavior of the gateway when it belongs to more than 2 piconets).

(ii) The gateway can be modeled as a *shared processor*. The gateway shares its time between each of its piconets. The gateway may be viewed as a processor servicing each of its piconets in a Round-Robin manner.

(iii) The gateway behaves as a *service center with multiple servers*. When the gateway "visits" a piconet, let the time it spends in each piconet be T Bluetooth slots. A maximum of T Bluetooth packets may be accommodated in these T slots (we assume for the sake of convenience that Bluetooth packets are 1 slot in length; the analysis would be very similar if the packets were of 3 or 5 slots).

Thus, the number of packets that the gateway transfers each time it visits a piconet depends upon the value of T and the length of the gateway queue. This system behaves like a multiple server system, where each server can serve a single customer (a 1-slot Bluetooth packet) in T time slots, and the number of servers is T. The service rate μ' for a single server in the service center is thus given by:

$$\mu' = (BW*x)/T \qquad (1)$$

Combining the above three observations, we model the gateway as a "processor-sharing multiple-server service center", where each server has a service rate as given in Eq. 1. The service rate for the gateway, μ, is thus given by:

$$\mu = (BW*x*k)/T \qquad 0<=k<=T$$
$$\mu = (BW*x) \qquad T < k \qquad (2)$$

where k is the no. of packets in the gateway's queue.

3.2. Analytical Model of a Bluetooth scatternet

We now develop an analytical model for a Bluetooth scatternet, treating the set of gateways as a network of queues. The product-form solution for an open Jacksonian network of queues is given by:

$$p(k_1, k_2, \ldots, k_n) = p_1(k_1)\, p_2(k_2) \ldots p_n(k_n) \qquad (3)$$

where k_i is the number of customers at node i, $p_i(k_i)$ is the marginal distribution of finding k_i customers at node i , and n is the number of nodes.

Moreover, of the four types of service centers for which the product form applies [10], the gateway is a node of Type II: it is a shared processor and its service process has a rational Laplace transform. The extension of Type II service centers to include multiple servers (as is the case with the gateway) is given in [11]. The equilibrium probabilities at a node are given by:

$$p(n) = p(0) \prod_{j=1}^{n} (\max(T, j))\ \frac{(\lambda/\mu)^n}{n!} \qquad (4)$$

where λ is the arrival rate at the node, μ is the service rate of a single server of the node and T is the number of servers.

We now apply Eq. 4 to a scatternet and derive a relation between average delay and throughput. Let M be the number of links (i.e., gateways) in the network. Let γ be the total traffic to the network and λ_i be the traffic rate at link i. Using Eq. 4, we get:

$$p(k) = \frac{(p(0) * (\lambda/\mu)^k)}{k!} \qquad 0< = k <= T$$
$$\qquad (5)$$
$$p(k) = \frac{T^T\, p(0)\, (\lambda/\mu T)^k}{T!} \qquad T < k$$

Using Eq. 5, we get:

$$p(0) = \left[(\lambda/\mu T)^T\, \frac{(\lambda/(\mu T - \lambda))\, T^T}{T!} + \sum_{k=0}^{T} \frac{(\lambda/\mu)^k}{k!} \right]^{-1} \qquad (6)$$

The average number of packets on link i, N_i is given by:

$$N_i = \Sigma\, (k * p(k)) \qquad (7)$$

From [10], denoting the average delay by T_{avg}, we know that:

$$T_{avg} = \sum_{i=0}^{M} (\lambda_i/\gamma * T_i) = \sum_{i=0}^{M} (N_i/\gamma) \qquad (8)$$

Equation (8) gives the relation between the throughput and the average delay in a scatternet.

4. Results

In this section, we apply the analytical model in two typical applications, each having a different traffic pattern and determine the delay-throughput characteristics for the topologies, identify topologies that produce better delay-throughput characteristics.

4.1 Uniform Traffic Pattern

We first consider an application of Bluetooth scatternets where any node in the network may have an equal tendency to communicate with any other node. In such an environment, any user will send a more-or-less equal amount of data to any other user and the traffic in the network is uniform in nature. It behooves us, given a uniform traffic pattern, to consider symmetric topologies (as shown in Fig 2) that could be created by making all piconets have the same number of slaves and gateways and connecting the gateways appropriately. We consider a fixed number of nodes, N, which may be connected using piconets with different values of 'i', the number of gateways per piconet and 'j', the number of piconets per gateway.

In some topologies, the number of nodes may not be exactly equal to the value of N, since a certain value of i and j may not allow all values of N. In such cases, we assume that the network has the closest number of nodes, smaller than N, that the values of i and j allow. To accommodate this in the

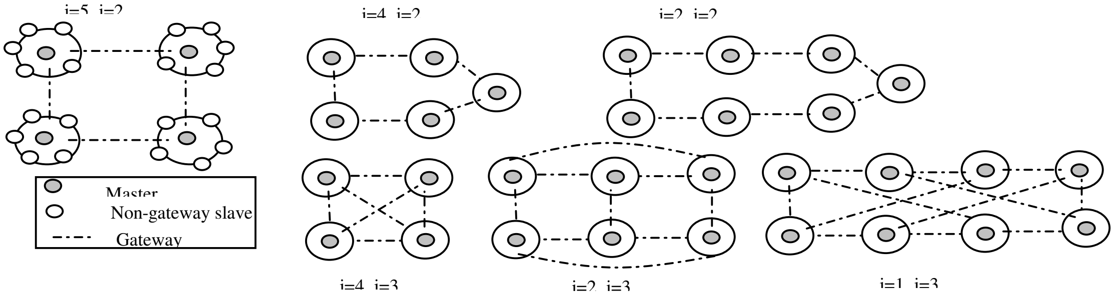


Fig 2: Different topologies formed by varying values of i and j when N = 28

analysis, we adjust the arrival rate and the service rate of a gateway accordingly.

Due to the uniform traffic pattern, all non-gateway slaves send the same amount of data. Thus, our scheduling policy gives each non-gateway slave the same amount of bandwidth. Also, due to the symmetric topologies, each gateway is also given the same amount of bandwidth. Since a gateway is expected to carry more traffic than non-gateway slaves, it requires more bandwidth than non-gateway slaves. We assume that the gateway is given a polling priority of 'p' with respect to the non-gateway slaves, which means that it gets 'p' times the bandwidth allocated to non-gateway slaves. Thus, if there are 'x' non-gateway and 'y' gateway slaves in a piconet, the bandwidth (service rate) given to a gateway in a piconet, μ is given by (from Eq 2):

$$\mu = (BW * x) = (BW/(x/p) + y) \qquad (9)$$

where BW is the Bluetooth bandwidth.

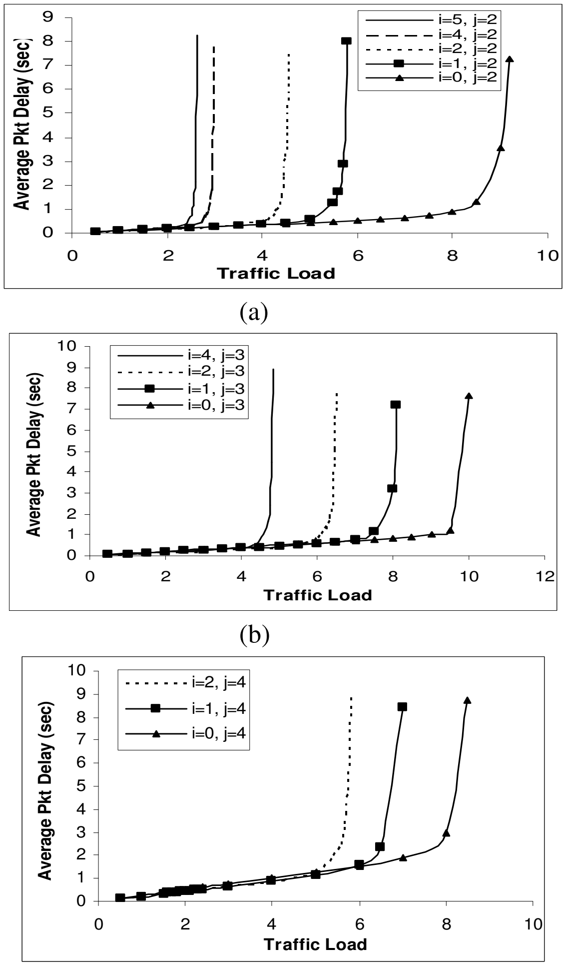
4.1.1 Comparison of Topologies

Figs 3 (a), (b) and (c) show the delay-throughput characteristics for different values of i when j = 2, 3 and 4 respectively, with p = 1. It can be seen from the figure that for the type of applications considered, networks with a smaller number of slaves (and hence larger number of piconets) show smaller average delays. Moreover, the breakdown point, i.e., the knee of the curve, for networks with smaller number of slaves is larger than that for networks with larger number of slaves. These networks are thus, also more stable. From an intuitive point of view, a smaller number of slaves means a larger bandwidth for the gateway and hence, a larger service rate and lower delays on the gateway link.

Moreover, as the number of gateways is increased from 2 to 3, the delays get smaller and the breakdown point becomes larger. On the one hand, the gateway bandwidth decreases when j is increased from 2 to 3, but on the other hand, there is reduced traffic on each gateway link due to these reasons:

- In topologies with j=3, the avg number of hops between two nodes is reduced due to a larger number of gateways (more connectivity). This means that the total traffic on the network is less as compared to topologies with j=2.
- Topologies with j=3 have a larger number of gateways than those with j=2. This means there are more gateways to carry the traffic and lower traffic on each gateway. These two reasons more than make up for the decreased gateway b/w and hence, system performance is better.

For topologies with j=4, on the other hand, the effect of the above two reasons is not enough to counter the reduced bandwidth when compared with topologies with j=3. These topologies thus, show lower performance than those with j=3. In fact, we observed that topologies with j > 4 show a worse behavior than those with j = 4. Thus, we see that there is an optimum number of gateways for the application. Another important point is that the above analysis also enables one to determine the maximum load a network may accept before delay deteriorates precipitously, i.e. the optimal point to operate a network [11] (which is the knee of the curve).



(a)

(b)

(c)

Fig 3 (a), (b) and (c): Delay-throughput characteristics for different values of i when j = 2, 3 and 4

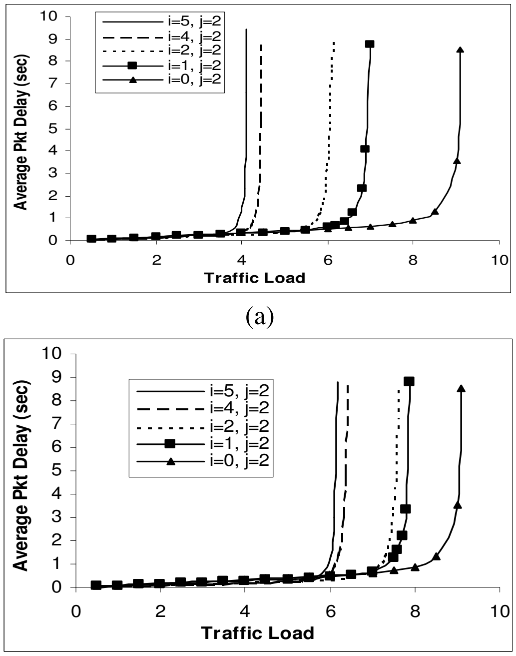
	Breakdown point = 6sec	Breakdown point = 8sec	Breakdown point = 10sec
i = 5, j = 2	4.5	14.5	-
i = 2, j = 2	1.8	6	-
i = 1, j = 2	0.9	2.9	-
i = 4, j = 3	1.5	3.1	9
i = 2, j = 3	0.75	1.55	4.5
i = 1, j = 3	0.37	0.77	2.3

Table 1: Gateway priorities needed to achieve certain breakdown points for different topologies

4.1.2 Effect of varying the gateway priority

We now show the effect of giving different priorities to gateways, i.e., changing the value of p in Eq. 9. Fig 4 (a) and (b) show the characteristics when p=2 and p = 5 respectively. The results show that a higher priority for the gateways tends to decrease the delays. As earlier, a smaller number of slaves still gives lower delays and higher breakdown points. In fact, the priority can only be increased to a certain point; if the priority is increased beyond a value, the slave may become a bottleneck and the gateway may cease to be a bottleneck. This will violate the basic premise of the model, which assumes that the gateways are the bottlenecks in the system.

Another observation is that the breakdown point increases with an increase in priority of the gateway. Table 1 shows the priority required for various topologies to achieve a certain breakdown point when N =28. The entries with a '-' imply that this breakdown point cannot be achieved for the topology. Thus, topologies with j=2 cannot achieve a breakdown point of 10sec, whereas topologies with j=3 can. Also, it can be seen that a smaller value of i requires a lower priority to achieve a certain breakdown point.



(a)

(b)

Fig 4 (a) and (b): Characteristics for p =2 and p=5

4.2 Centralized Traffic Pattern

We now consider a second application of Bluetooth scatternets where each node in the network wishes to communicate with one central server. Traffic rates from all nodes are assumed equal. Such a traffic pattern may be typical of a factory or a warehouse where these nodes are used in tasks like inventory tracking. Since each node sends an almost equal amount of data to the server, it needs to be given the same bandwidth to the central server.

We consider a topology with (i=0, j=2, N = 29), as shown in Fig 5. We assume, as earlier, that a gateway belongs only to two piconets. G1, G2 and G3 represent gateway categories that have different traffic and service rates. As shown in the figure, the topology consists of various stages. Note that the topology is symmetric at each level (at each level, piconets have the same number of slaves and gateways). If a certain topology (number of slaves and gateways per piconet) shows best delay-throughput characteristics, then applying the same topology at each stage gives a topology that is better than any other. We, thus, have the same topology at each level.

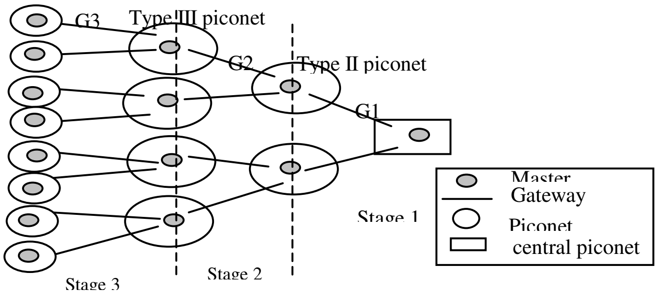


Fig 5: Central server topology with i=0 and j=2

We now analyze the i=0, j=2 topology. BW refers to the Bluetooth bandwidth, while BW_{Gi} is the bandwidth required by a gateway so that each node gets the same bandwidth to the central server. λ_{Gi} and μ_{Gi} are the traffic rate and service rate respectively of gateway G_i.

G3 needs to carry traffic (to the central server) for one master node and itself. Thus, G3 needs twice the bandwidth as a non-gateway slave node. If a node sends traffic at the rate of x, then $BW_{G3} = 2x$. Now, G2 needs to carry traffic for two gateways of the G3 category, one master node and itself. Thus, $BW_{G2} = (2*BW_{G3}) + 2 = 6x$. Similarly, $BW_{G1} = 14x$. There are two G1s at the central piconet and each carries traffic equal to 14x. Thus, each gets 14/28 of the central piconet's bandwidth (the central master's polling). Thus $\lambda_{G1} = 14x$; and $\mu_{G1} = (14/28) * BW$.

Now, at piconet of type II, G1 gets 14/28 of the polling. Thus, bandwidth given to each gateway, G2 = (1 – 14/28)/2 = 7/28. Each gateway G2 carries 6x of the traffic => $\lambda_{G2} = 6x$; $\mu_{G2} = (7/28) * BW$. At piconet of type III, G2 gets 7/28 of the polling. Thus, bandwidth given to each gateway G3 = (1-7/28)/2 = 10.5/28. Each gateway G3 carries 2x of the traffic. => $\lambda_{G3} = 2x$; $\mu_{G3} = (10.5/28) * BW$. Total traffic in the network is $\gamma = 28x$ (each node sends x to the master of the central piconet).

Fig 6 shows the delay vs. traffic load curves for different values of i (while keeping j fixed), with N= 29. It can be seen that for the type of applications considered, networks with a larger number of slaves per piconet (and hence a smaller number of piconets) show smaller average delays. In this application, gateways that serve a small number of slaves have a high capacity but a small amount of data to transfer. This means that a large part of the gateway capacity is wasted and there is no gain from the large capacity of the gateway. On the other hand, a small number of slaves leads to larger no. of average hops traveled by a packet and higher delays.

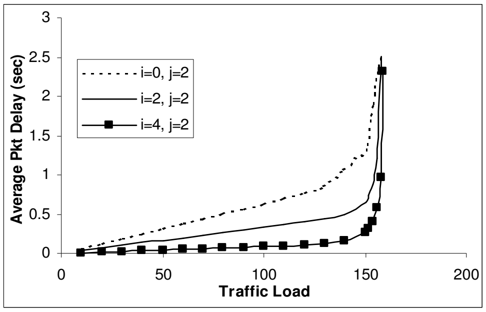


Fig 6: Characteristics when varying values of i with j=2

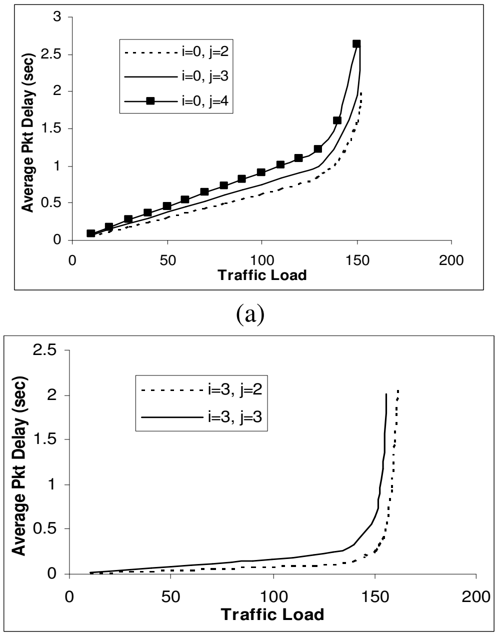
Figs 7 (a) and (b) show the effect of varying j on the delay-throughput profile. Networks with a smaller number of gateways show smaller delays and higher breakdown points. A smaller number of gateways leads to a higher capacity per gateway. The effect, though, is very marginal, since giving gateways a large capacity may not be very beneficial, as explained above. Thus, increasing the number of gateways does not have too much of an effect, though, a smaller number of gateways shows a better behavior. Also, the breakdown points for networks with different numbers of slaves are almost the same.

We conducted the same tests for different number of nodes, varying from N=25 to N=60. The results were quite similar to the results for N=29. We can thus, conclude, that for applications with centralized traffic, the results shown for N=29 are valid, in general. We also validated the above results with simulation experiments, which show a very close matching with the analytical results.

5. Conclusions and Future Work

In this paper, we addressed several issues related to topology of scatternets. We presented an analytic approach to determine the number of non-gateway and gateway slaves per piconet to ensure acceptable delay characteristics. We developed a queuing model for a scatternet and validated the model via simulations. We studied two typical applications of Bluetooth scatternets with different traffic patterns. In each application, we used analytic results to compare delay-throughput characteristics of various topologies and determine the optimal point to operate the network.

We intend to generalize, in the near future, our analytic model to study topologies where a gateway is shared among an arbitrary number of piconets. We also intend to include the effects of various scheduling schemes. For example, when the traffic is non-uniform, a dynamic scheduling scheme could be used to modify the bandwidth fraction allocated to the gateways based on traffic patterns. More sophisticated models of "processor sharing" and the effect of interference on a gateway are also planned.



(a)

(b)

Fig 7 (a) and (b): Characteristics for different values of j

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