Interconnection of networks: performance evaluation model of internet node

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We analyze a system composed by local area networks or metropolitan area networks interconnected through an internet node. We consider a specific network, Fasnet, which has linear (bus) topology and implicit token passing medium access control (MAC) protocol.

We propose a stochastic model to evaluate performance indices of the interconnected system. The evolution of the system, because of MAC protocol characteristics, can be represented by a discrete-time periodic Markov chain. We provide an efficient solution technique for the computation of performance indices.

We analyze the model of interconnected networks by varying a wide range of system parameters and, by comparing the results of the approximate model with simulation model, we observe a good accuracy of the proposed model.

1. INTRODUCTION

An important issue in the development of computer networks concerns with network interconnection, which allows communication among users located on different networks and resources’ sharing. Network interconnection raises many technical problems, including, for example, congestion control, routing, fragmentation, and performance issues. Critical components of the system are the mechanisms for achieving interconnection and their performance. In this paper we consider a system composed by local area networks (LAN) or metropolitan area networks (MAN) interconnected through an internet node. We propose a stochastic model to evaluate performance indices of the interconnected systems, including the communication delay between networks due to the internet node.

We consider a specific network, Fasnet [7,8], which has linear (bus) topology and implicit token passing medium access control (MAC) protocol. Because of the MAC protocol characteristics, it is possible to describe system’s behavior by a discrete-time periodic Markov chain, for which we provide an efficient solution technique for the computation of performance indices. The comparison between this approximate analytical solution with simulation, over a wide range of system parameters, shows a good accuracy of the proposed model. The paper is organized as follows. Next Section is dedicated to system’s description, while the mathematical model is introduced in Section 3 where an efficient solution technique for the computation of performance indices is also provided. Section 4 deals with model validation in terms of comparison between the approximate and the simulation model. Finally, conclusions and further developments are discussed in Section 5.

2. NETWORK INTERCONNECTED SYSTEM

We consider a system formed by local area networks (LAN) and/or metropolitan area networks (MAN) interconnected through internet nodes or gateways. Local Area Networks are still evolving rapidly, and lead to the development of Metropolitan Area Networks whose main purpose is to provide high speed transmission (typically speeds are 10^6 Mbit/sec) for integrated traffic services such as data and video/voice. The internal transmission speed of most LAN’s requires a high speed interconnection component in order to bound the communication delay between networks. Therefore high speed LAN’s and MAN’S MAC-level protocols are characterized by fairness of the access scheme, low bounded access delay, support of several traffic types or user classes, etc. [2,11]. Several authors proposed different MAN’s, such as Fasnet [7,8], Expressnet [9], FDDI [10], DQDB [4,5].

We consider a MAN’s interconnected system composed by Fasnet networks, which are characterized by linear (bus) topology and implicit token passing MAC protocol. Fasnet network architecture is based on a dual bus topology as shown in Fig. 1, where Sj denotes the i-th station (1<i<n). Each pair of stations is connected through the two lines and, for line A, Sj is referred to as the head station and Sb is the end station, while, for line B, the assignment is reversed. The first station in each channel exercises centralized access control, as described in [7]. Fasnet operates as a synchronous and cyclic network; each head station transmits a synchronization code at regular intervals, which allows the other stations to synchronize on it.

During a cycle, the stations send packets but, to guarantee fairness, each station, Sj, can not send more than a certain number of packets; this threshold value is denoted by Pj max, 1<i<n. A cycle is the time it takes all stations to send their packets and, since both the number of packets sent during a cycle and the number of active stations are variable, then also the cycle time is variable. When all the stations have sent their packets, an unused frame will proceed down the line; when the last station on the line (A or B) detects the empty frame, it send back (on the other line) to the first station (head station) an end bit. Upon receiving this end bit, the head station starts a new cycle, thus allowing stations to transmit again. Note that, at the end of each transmission period, there is a period of inactivity which ends when the end bit reaches the head station. Hereafter, we shall refer to this period as the sojourn time of the system.

Let us define the following system’s parameters:

\( v = \text{speed of propagation on the line (m/s)} \)
\( W = \text{Line capacity (bit/s)} \)
\( L = \text{line length (m)} \)
\( F = \text{frame size (bits)} \)
\( M = \text{number of active stations} \)

If each station Sj is allowed to transmit, during a cycle, its maximum number of packets, \( f_j \text{ max} \), then we can compute the cycle time \( t_c \) (sec), and the transmission time \( t_b \) (sec) as follows:

\[
\begin{align*}
\tau_c &= \sum_{i=1}^{M} p_i \text{ max} (F/W) + 2 (L/V) + (F/W) \\
\tau_b &= \sum_{i=1}^{M} p_i \text{ max} (F/W)
\end{align*}
\]

Finally, the network utilization factor \( \rho \) is defined as:

\[
\rho = \frac{\tau_b}{\tau_c}
\]

In the next section, we provide an approximate mathematical model to evaluate system performance indices.

3. MATHEMATICAL MODEL

We shall now define a stochastic model to evaluate performance indices of the interconnected system described in the previous section, and an efficient solution technique for the computation of performance indices of the system, such as mean queueing time of the interconnection node and the communication delay between networks due to the internet node. Consider a system composed by a single interconnection node, or gateway (G), which allows \( N+1 \) Fasnet MAN (denoted by Fasnet, etc.),
Consider an interconnection system with the following characteristics:
- $P$: the phase-difference between networks' transmission cycles, which represents the difference, expressed as number of slots, between the beginning of the $n$-th transmission cycle of Fasnet $i$ network ($1 \leq n \leq N+1$) and of a reference network.
- $N$: number of interconnected networks;
- $\rho$: network utilization factor.

By analyzing the behavior of the interconnected system, optimal conditions for phase-difference parameter $P$ can be derived, with respect to performance indices of the interconnected system. These indices depend on other system parameters [1]. We shall not deal with this problem which is beyond the scope of the paper.

The Fasnet MAC protocol is characterized by a cyclic behavior:

- each cycle $T_c$ includes a transmission period $T_b$, when stations are allowed to transmit, and a sojourn time $T_s$, when transmission is not allowed. Therefore one can write

$$T_c = T_b + T_s$$

and, by the network utilization factor definition, one obtains

$$T_s = \left(1 - \frac{\rho}{\rho_{\text{max}}} \right) T_b = T_b (1 - \rho) \rho$$

(2)

We shall consider a system with the following network characteristics:
- line capacity $W = 150$ Mbps
- slot dimension $F = 1024$ bits
- sojourn time $T_s = 800$ usec
- maximum transmission period $T_b_{\text{max}} = 800$ slots.

Hereafter we shall consider quantities $T_c$, $T_b$ and $T_s$ expressed in number of slots instead of seconds.

From relation (2) one can derive that the utilization factor is bounded by

$$0 < \frac{\rho}{\rho_{\text{max}}} < 1$$

wherefrom one can derive the maximum utilization factor

$$\rho_{\text{max}} = 0.9$$

We assume that each Fasnet has the same cyclic characteristics, i.e., it produces cycles with the same number of slots, composed by $T_b$ full slots followed by $T_s$ empty slots. Each slot can contain a packet whose destination can be an internet packet or a single output stream of the Fasnet (intranet traffic) or a station on one of the other interconnected MAN's (intranet traffic). Let $P_{\text{int}}$ denote the probability that a MAN slot contains an internet packet. We assume the same internet probability for each MAN.

The cyclic behavior of a MAN is represented in Fig.2, where $b_n$ ($= n \rho_{\text{int}}$) and $c_n$ ($= (n+1) \rho_{\text{int}}$) denote, respectively, the beginning and the end of cycle $n$, while $c_n$ denotes the end of the $n$-th transmission period $T_b$, and the beginning of the $n$-th sojourn time $T_s$. Note that in the example reported in Fig.2 we have $T_s = T_c$, which is related to a high utilization factor. Indeed, it is easy to derive from formula (2) the following relations between the utilization factor $\rho$ and the duration of transmission period $T_b$:

$$T_b = \frac{\rho}{1 - \rho}$$

Each MAN is associated both to MAN's (input) and to MAN's (output). The interconnection node $G$ receives packets from each port in an input module, where the destination network is determined. Then the packet is sent to the "Switching Fabric" which determines the physical path to the output port of the destination MAN, which is connected through the output module.

The internal structure of the Switching Fabric heavily affects system performance, especially depending on if either a single or multiple buffers and servers are used for each port [6]. We assume that a service center, formed by a server with a buffer, is associated to each output port, and a packet is delayed only if it is sent to a port which is already busy. An example of the Switching Fabric structure of node $G$ for three interconnected MAN's is illustrated in Fig.3.

Consider an interconnection system with the following characteristics:
- each Fasnet connected to the system has the same utilization factor $\rho$, and, consequently, the same cycle time $T_c$.
- each Fasnet has the same internet probability $P_{\text{int}}$ to send internet packets during the transmission period $T_b$; this probability is assumed to be uniformly distributed and independent of the state of node $G$.
- all the Fasnets are synchronized at slot time level.

Probability $P_{\text{int}}$ represents the overall internet traffic produced by each Fasnet, toward all the other Fasnets, and it is distributed among the networks according to a given distribution. Let $P_{\text{int}}$ denote the probability that an internet packet from Fasnet $i$ is destined to Fasnet $j$ ($1 \leq i < j \leq N+1$). For the sake of simplicity, here we shall assume the uniform distribution from each Fasnet, i.e.,

$$P_{\text{int}} = \frac{1}{N+1} \frac{1}{N+1}$$

The internet node model is composed by $N+1$ service centers, where the $i$-th service center is related to the internet traffic arriving from all the interconnected Fasnets and destined to Fasnet $i$ ($1 \leq i \leq N+1$). Since we assumed multiple output buffers in the internet node, one for each network, the analysis of the system can be reported to the analysis of the single service center which represents $N$ incoming Fasnets connected to a single output Fasnet, as shown in Fig.4. The figure also shows node $G$ model structure, which is introduced in order to simplify model analysis.

We assume that each service center schedules the packets in the queue according to the First Come First Served service discipline. Service time is equal to the slot transmission time. In this model we assume limited buffer capacity; however from model solution one can derive the appropriate buffer dimension which corresponds to a negligible packet loss rate. In order to analyze the introduced interconnection model, we decompose each service center in two components denoted by $G_{\text{in}}$ and $G_{\text{out}}$, respectively.

Component $G_{\text{in}}$ represents the behavior of the arriving internet packets to the service center, while component $G_{\text{out}}$ models the output of the internet node on the destination network, according to the MAC protocol characteristics. From the model viewpoint we can represent $G_{\text{in}}$ as the component with $N$ input Fasnet and a single output stream of internet packets which are directed to the $G_{\text{out}}$ component. $G_{\text{out}}$ includes the node buffer and transmits internet packet according to the output Fasnet protocol, as shown in Fig.4. Both $G_{\text{in}}$ and $G_{\text{out}}$ evolution are represented by discrete time periodic Markov chains [3], for which an efficient solution is provided. We shall now describe the two model components.

3.1 Model component $G_{\text{in}}$

In the analysis of the interconnected networks we have to consider the phase-difference parameters $P_i$ ($1 \leq i \leq N$), i.e., the difference among the beginning of transmission cycles of the $N$ input Fasnets. We shall now present the model for the synchronous case, that is when all the incoming Fasnets start the cycle at the same time ($PD_i = 0$, $V_i$). The model for the asynchronous case and its solution can be computed by using a similar scheme [1].

At each time the $N$ incoming Fasnets can produce an internet packet according to the cyclic behavior previously described. Let $<j>$ denote the network input state when $j$ of the $N$ input Fasnets are in the transmission period, $0 \leq j \leq N$. Let $b(j)$ denote the probability that $i$ internet packets arrive when there is a network input state $<j>$; this probability can be computed as follows:

$$b(j) = \left( \begin{array}{c} j \\ i \end{array} \right) \left( P_{\text{loc}} \right)^j \left( 1 - P_{\text{loc}} \right)^{j-i}$$

(3)

for $0 \leq j \leq N$, $0 \leq i \leq j$.

Therefore, at each time, if there is $j$ input Fasnet in transmission period, the output queue of node $G$ can be either decreased of one packet with probability $b(0)$ or increased of $i$ packets with probability $b(j)$, $0 \leq j \leq N$, $1 \leq i \leq j$.

The system behavior can be modeled by a discrete time Markov chain, whose steps correspond to packet arrivals from the input networks. Let $<i>$ denote the state of the system at time $i$ when there are $j$ packets in the queue ($i,j \geq 0$).

The proposed model is obtained by assuming a cyclic behavior of the system, which leads to a periodic Markov chain model. The following assumption derives from the cyclic behavior of the MAC protocol: we assume that at the end of the sojourn time the service center queue is always empty.

In a system with synchronized input Fasnet, during the sojourn time $T_s$, no packet transmission is allowed and, consequently, there are $T_s$ service
times during which the queue constantly decreases. Therefore the empty-
queue assumption at the end of sojourn time seems to be acceptable.
In a system where the input Fasnet are not synchronized one can consider
that this is not a natural assumption, because during the sojourn time of
the reference Fasnet the queue is not always guaranteed to constantly
decrease. However it is possible to derive the conditions under which
this empty-queue assumption is verified in terms of internet traffic and
network utilization; these conditions are discussed in [1] and it has been
shown that the ranges of parameters values that verify this assumption
include most of the real systems.
By using this assumption we obtain a periodic Markov chain which
represents the system cyclic behavior. Therefore the proposed model is
approximate and its accuracy is evaluated both by testing the empty-
queue assumption, and by comparing the analytic model with a
simulation model, as described in the next Section.
In the case of synchronized input Fasnet there are only <0> network
input states during the sojourn time \( t_b \) and <N> network input state
during the transmission period \( t_T \). Therefore, at each time \( i \), the service
center queue increases of at most \( N-1 \) packets, and its range of values is
\([0, i(N-1)] \), \( 0 \leq i \leq t_b \). The Markov chain state diagram is illustrated in
Fig.5, and its state space \( E \) is given by
\[
E=\{(0,1), (1,1), ..., (t_b, tb(N-1)) \}
\]
(4).
The transition probability matrix \( P \) can be partitioned into submatrices
\( M_i \), \( 1 \leq i \leq t_b \). Fig.6 shows the internal structure of square
submatrices \( M_i \), \( 1 \leq i \leq t_b \), of order \( |\{(i,N-1)\}| \), while submatrix
\( M_{t_b+1} \) is a unitary vector with \( t_b(N-1)+1 \) components. The Markov
chain has period \( \delta=t_b+1 \), and its state space \( E \), defined by formula (4),
can be partitioned in the following classes:
\[
C^i=\{(0,i), (1,i), ..., (t_b,i(N-1)) \}
\]
(5).
Let \( \pi \) denote the Markov chain probability vector, whose component \( \pi^i \)
denotes the probability of state \( (i,J) \in E \). Vector \( \pi \) can be obtained as
the unique solution of the following linear system [3]
\[
\begin{align*}
\pi^0 & = 1 \\
\pi^i_j & = (b(0,N)\pi^i_{j-1} + b(0,N)\pi^i_{j-1})/\sum_{j'=} \pi^i_{j'}. \\
\pi^i_j & = \sum_{j=} b(j,N)\pi^i_{j+1} \\
0 \leq i \leq t_b & , 1 \leq j \leq (N-1)
\end{align*}
\]
(6)
where probabilities \( b(i,j) \) are given by formula (3).

Finally, by using this probability distribution one can evaluate the probability
that an internet packet has to be transmitted on the output Fasnet of the interconnected system. Let \( \text{Prob}(i,0) \) denote the probability
that at time \( i \) in the cycle no internet packet is produced by the
interconnection node \( G \), \( 0 \leq i \leq t_b \). This probability only depends on the
queue length at time \( i-1 \) and on the probabilities that no packets arrive at
time \( i \). In other words one can compute \( \text{Prob}(i,0), 0 \leq i \leq t_b \), as follows:
\[
\text{Prob}(i,0)=\pi^i_0 \cdot b(i,0)
\]
(7.1)
where \( B(j,i) \) is the network input state at time \( i \) and probabilities \( \pi^i_0 \)
and \( b(0,i) \) are given by formulas (6) and (3), respectively.
Similarly, probability \( \text{Prob}(i,1) \) that an internet packet has to be sent on
the output network at time \( i \) in the cycle, \( 0 \leq i \leq t_b \), is given by
\[
\text{Prob}(i,1)=1-\text{Prob}(i,0)
\]
(7.2)

3.2 Model component \( G_{\text{Out}} \)
Model component \( G_{\text{Out}} \) receives the stream of internet packet from component \( G_{\text{In}} \) that have to be transmitted on the output Fasnet, as shown in Fig.4. This component can be analyzed as a station on the
output Fasnet network with a special arrival distribution defined by the
output probability distribution obtained by the analysis of component
\( G_{\text{In}} \), given by formulas (7.1) and (7.2).
We assume that the interconnection node is the first station of the
output Fasnet, which has constant parameters \( \tau_c \), \( \tau_b \) and \( \tau_f \). Therefore the internet packets received from the input Fasnet network through
model component \( G_{\text{In}} \) can be transmitted on the output network only
during the transmission period \( \tau_b \). On the contrary, if the output Fasnet is
in the sojourn time, then the arriving packets are enqueued in the
buffer where they wait the next cycle to be transmitted. A transmission
period can be completed either if \( P_{\text{max}} \) packets have been transmitted or
if the buffer is empty. We shall assume a finite buffer dimension
denoted by \( B \).
The \( G_{\text{Out}} \) component is analyzed in terms of queue length distribution,
from which other performance indices can be derived.
The system behavior can be modeled by a discrete time Markov chain,
whose state is denoted by \( (i,J) \) when there are \( J \) packets in the
buffer \( 0 \leq J \leq B \), and the output Fasnet network is either in in
the transmission period \( \tau_b \) or in sojourn time \( \tau_s \). In other words,
when \( i=\tau_b \) then packets can be transmitted, while they have to wait if
\( i=\tau_s \). Note that, in this case, the end of a given cycle (at time \( \tau_s \))
coincides with the beginning of the successive cycle (at time \( 0 \)).
As for the previous case, the proposed model is a periodic Markov chain
with state space \( E=\{(i,J) \} \mid 1 \leq i \leq t_b, 0 \leq J \leq B \), \( i=\tau_b \) or \( i=\tau_s \),
and transition probability matrix \( P \). The Markov chain has period \( \delta=t_b+1 \) with classes:
\[
\begin{align*}
\delta_1 & =\{(i,B,T) \} \mid 1 \leq i \leq t_b, 0 \leq T < B \} \\
\delta_2 & =\{(i,B,T) \} \mid 1 \leq i \leq t_b, T = B \}
\end{align*}
\]
For \( i=1 \) and \( 2 \leq i \leq t_b \), \( \delta_1 \) class have been divided into subcategories
\( \delta_1^1 \) and \( \delta_1^2 \), respectively.
Let \( \delta_2 \) denote the Markov chain probability vector, whose component \( \pi^i \)
denotes the probability of state \( (i,J) \in E \). Vector \( \pi \) can be obtained as
the unique solution of the following linear system [3]
\[
\begin{align*}
\pi^0 & = 1 \\
\pi^i_0 & = \sum_{j=0}^{B} b(j,i)\pi^i_{j-1} + b(0,i)\pi^i_{j-1} \\
\pi^i_j & = \sum_{j'=0}^{B} b(j',i)\pi^i_{j'+1} \\
0 \leq i \leq t_b & , 1 \leq j \leq B
\end{align*}
\]
(8)
where probabilities \( b(i,j) \) are given by formula (3).

3.3 Performance indices
By using the probability distribution given by formula (9), obtained by
the combination of the two stochastic models, the performance indices
of the interconnected system can be computed, such as the mean queue
length and the communication delay due to the internet node.
The interconnection node mean queue length at time \( i \) in the cycle,
denoted by \( E(i), 1 \leq i \leq t_b \), can be computed as follows:
\[
E(i)=\sum_{i=0}^{t_b} E(i)\pi^i_i
\]
(7.1)

Transition probability matrix \( P \) shows a block structure with
submatrices \( M_i \), \( 1 \leq i \leq t_b \), as shown in Fig.8. Similarly to the previous
model, also solution \( \pi \) can be recursively computed as follows:
\[
\begin{align*}
\pi^i & = \pi^i \cdot M_{i-1} \\
\sum_i \pi^i & = \delta_c
\end{align*}
\]
(9)
The entire model has been validated by comparing the estimations of the FODI, DQDB, and Fasnet networks. The comparison with results provided by simulation begins at the end of a new cycle. The internet queue contains a specific value during the cycle. Denoted by Delay(i), and expressed in terms of numbers of slots, can be computed as follows:

$$\text{Delay}(i) = \left\{ \begin{array}{ll} \left( E(i) + (\tau_c \cdot \rho \cdot \Gamma_{\max}) \sum_{j=0}^{\Gamma_{\max}} \Gamma_{i,j,0} + (\tau_c \cdot \rho) \sum_{j=0}^{\Gamma_{\max}} \Gamma_{i,j,W} \right) & \text{if } 1 \leq i \leq \Gamma_{\max} + 1, \quad i = T \\
\left( \tau_c \cdot \rho \cdot \Gamma_{\max} \right) & \text{if } i = W \\
0 & \text{otherwise} 
\end{array} \right.$$ (11)

where E(i) is given by formula (10).

4. MODEL VALIDATION

This section is devoted to the validation of the mathematical model described in the previous Section. For sake of simplicity, we analyze only the synchronized case; in [1] the general asynchronous case are also examined.

With regard to the model component GIN, we have tested, by simulation, the validity of the empty-queue assumption at the end of the sojourn time. More in details, we have estimated the probability distribution of the queue length (internet queue length) at the beginning of a new cycle (starting at the end of the sojourn time). The experiments have been performed for several values of system parameters. Tables I and II show the simulation results respectively when three and four Fasnet are connected. Each element of the tables denotes the probability that, at the beginning of a new cycle, the internet queue contains a number of packets less or equal to a specific value S, for S = 0, 1, 2, ..., 10. Since no value in the tables exceed 0.906, we can consider our assumptions reasonable and we can neglect the contribution of the discarded slots at the end of the cycle to the evaluation of performance indices.

After having verified the validity of the empty queue assumption, the entire model has been validated by comparing the estimations of the average queue lengths of the internet node obtained by simulation and by the solution of the approximate model. More specifically, the analytical mean queue length at time i in the cycle, E(i), has been evaluated, by using formula (10). Table III shows the results of one experiment of one interconnected system with two input Fasnet and $\rho = 0.7$. We have reported the endpoints of the confidence intervals (the confidence level is 0.9) and the values provided by the approximate method. Experiments have been performed for various values of system parameters and the comparison between results shows that the proposed approximated analytical model is appropriate to evaluate system performance measures.

5. CONCLUSIONS

In this paper we have provided an approximate mathematical model to estimate the performance indices of an internet node which interconnects Fasnet networks. The comparison with results provided by simulation models have shown that the approximate model works quite well for a wide range of system parameters. Moreover, the proposed model solution can be efficiently computed. Future works will concern with the extension of the model to other MAN/LAN cyclical protocols (such as FDDI, DQDB) and to the generalization to systems with more than one internet node and with general interconnection topology.

### Table I - Probability distribution of internet queue length at the beginning of the cycle for a three-node interconnection system

<table>
<thead>
<tr>
<th>( S )</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
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<tbody>
<tr>
<td>0</td>
<td>0.954</td>
<td>0.908</td>
<td>0.944</td>
<td>0.992</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.976</td>
<td>0.918</td>
<td>0.948</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.978</td>
<td>0.924</td>
<td>0.962</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3</td>
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<td>0.944</td>
<td>0.966</td>
<td>1</td>
<td></td>
</tr>
<tr>
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<td>0.992</td>
<td>0.948</td>
<td>0.972</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.996</td>
<td>0.954</td>
<td>0.976</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.998</td>
<td>0.966</td>
<td>0.982</td>
<td>1</td>
<td></td>
</tr>
<tr>
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<td>1</td>
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<td>0.986</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>8</td>
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<td>0.988</td>
<td>1</td>
<td></td>
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<tr>
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<td>0.988</td>
<td>1</td>
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REFERENCES

### Table I

<table>
<thead>
<tr>
<th>P</th>
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<th>0.4</th>
<th>0.5</th>
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<th>0.9</th>
</tr>
</thead>
<tbody>
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<td>$R_{loc}$</td>
<td>1</td>
<td>0.78</td>
<td>0.62</td>
<td>0.52</td>
<td>0.45</td>
<td>0.39</td>
<td>0.35</td>
</tr>
</tbody>
</table>

| S=0 | 1   | 0.988 | 0.976 | 0.92  | 0.947 | 0.98  | 1     |
| S=1 | 1   | 0.99  | 0.984 | 0.927 | 0.953 | 0.983 | 1     |
| S=2 | 1   | 0.994 | 0.992 | 0.927 | 0.96  | 0.983 | 1     |
| S=3 | 1   | 0.998 | 0.992 | 0.927 | 0.967 | 0.987 | 1     |
| S=4 | 1   | 0.998 | 0.992 | 0.927 | 0.967 | 0.987 | 1     |
| S=5 | 1   | 0.992 | 0.953 | 0.98  | 0.988 | 1     |
| S=6 | 1   | 0.992 | 0.986 | 0.993 | 0.988 | 1     |
| S=7 | 1   | 0.992 | 0.96  | 1     | 0.988 | 1     |
| S=8 | 1   | 0.996 | 0.967 | 1     | 0.99  | 1     |
| S=9 | 1   | 0.996 | 0.967 | 1     | 0.997 | 1     |
| S=10| 1    | 1     | 0.987 | 1     | 1     | 1     |

- Table II - Probability distribution of internet queue length at the beginning of the cycle for a four-node interconnection system.

<table>
<thead>
<tr>
<th>time</th>
<th>$i=0$</th>
<th>$i=1$</th>
<th>$i=4$</th>
<th>$i=8$</th>
<th>$i=12$</th>
<th>$i=14$</th>
<th>$i=16$</th>
<th>$i=18$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim L.B.</td>
<td>3.380</td>
<td>2.789</td>
<td>1.552</td>
<td>1.256</td>
<td>0.842</td>
<td>0.808</td>
<td>1.193</td>
<td>1.796</td>
</tr>
<tr>
<td>Sim U.B.</td>
<td>3.548</td>
<td>2.934</td>
<td>1.673</td>
<td>1.388</td>
<td>0.923</td>
<td>0.893</td>
<td>1.271</td>
<td>1.896</td>
</tr>
<tr>
<td>Appr.</td>
<td>3.350</td>
<td>2.765</td>
<td>1.401</td>
<td>0.875</td>
<td>0.711</td>
<td>0.724</td>
<td>1.244</td>
<td>1.824</td>
</tr>
</tbody>
</table>

- Table III - Mean queue length at time $i$ obtained by simulation and by the approximate model.

- Fig. 1 - The Fasnet topology.
- Fig. 2 - MAN behavior with internet traffic.
- Fig. 3 - Switching Fabric structure.
- Fig. 4 - Single service center network interconnection model.
- Fig. 5 - State diagram of the Markov chain for $G_{in}$ component.
FIG. 6 - Transition probability matrix of the Markov chain for $G_{in}$ component (a) matrix partition; (b) submatrices structure -

$$
\begin{pmatrix}
0 & 1 & 2 & \cdots & \tau_{\omega} & \tau_b \\
0 & M_1 & & & & \\
1 & & M_2 & & & \\
2 & & & M_3 & & \\
\end{pmatrix}
$$

$$
\begin{pmatrix}
1 & 2 & 3 & \cdots & \tau_{e} & \tau_c \\
1 & M_1 & & & & \\
2 & & M_2 & & & \\
3 & & & M_3 & & \\
\end{pmatrix}
$$

FIG. 7 - Example of state transition diagram of the Markov chain for $G_{out}$ with $\tau_c=4$, $P_{max}=2$, $B=1$ -

FIG. 8 - Transition probability matrix of the Markov chain for $G_{out}$ component -

\[1 - 1[M] = \begin{pmatrix}
0 & b_0 & b_1 & b_2 & \cdots & b_N \\
0 & b_0 & b_1 & b_2 & \cdots & b_N \\
\vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
0 & b_0 & b_1 & b_2 & \cdots & b_N \\
\end{pmatrix} \]