DESIGN AND ANALYSIS OF VERY HIGH SPEED NETWORK ARCHITECTURES

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ABSTRACT

This paper deals with communication architectures for very high speed networks. The use of high communication speed tends to increase the ratio between the end-to-end propagation delay and the packet transmission time. This increase restricts the utilization of the high system bandwidth in broadcast channel based systems causing a rapid performance deterioration.

This paper presents a communication system architecture characterized by the use of several parallel channels and an associated design of the nodes' channel interface. An analytic model of this system is developed through which the proposed system's performance is obtained. The derived performance shows that the proposed multichannel/node-interface architecture has a potential to significantly improve the system performance when compared to conventional single channel based systems. Furthermore, it is shown that for a given network configuration an optimal architecture can be found which simultaneously maximizes the system throughput and minimizes the average packet delay.

Keywords: High speed networks, Multichannel architectures, Channel interface design, Performance evaluation.
1. INTRODUCTION

The future communication environment will require the use of high capacity transmission systems. For applications such as computer to computer communication, LAN interconnections, voice messaging, video services or graphics, the aggregate transmission system bandwidth must be increased significantly beyond that found in currently prevailing networks.

"Very high speed" networks based on high bandwidth communication systems are subject of current research and development [1-7]. It was shown that the effect the increase in bandwidth has on the performance of the network depends on the network's communications system architecture.

Particularly it was shown that in communication systems based on a single broadcast channel, or bidirectional bus control (BBC) systems, the increase in channel bandwidth can be only partially utilized. In these systems as the bandwidth is increased the time required to transmit a packet becomes small relative to the time required for the packet to propagate across the network [8]. It is easy to see that the system capacity will thus decrease as the ratio of the signal propagation delay to packet transmission time increases [8,23]. A similar phenomenon can thus also be observed in low to medium speed networks in which the propagation delay to packet transmission time is high.

In this paper we propose an architectural approach for obtaining better utilization of high bandwidth communication systems. The proposed approach preserves the well known advantages of the broadcast bus [8,17] and has a potential for increasing the communication system's availability and reliability. We propose an architecture based on communication over several lower speed channels which are accessed by node channel interfaces requiring only partial multiplication of their transmit/receive functionality. The lower speed channels or subchannels can be either physically separate or obtained by dividing the frequency of a
single high speed channel, so that the bandwidth utilization on each subchannel is improved.

Currently, a number of existing baseband and broadband networks use parallel communication channels [3,9-11,20,21]. Multiple channel adapters and frequency agile high speed modems are commercially available [7]. Analysis of multi-channel Aloha systems [12,13] and CSMA systems [2,14] have shown that significant performance improvement and a number of implementation advantages can be obtained by the use of multiple channel architectures. However, for obtaining such improvement it has been assumed that each station is able to receive on an unlimited number of channels simultaneously. By assuming a bounded reception capability it has been demonstrated that the additional improvement obtained by channel multiplication is in fact gradually reduced as the additional bandwidth can be only partially utilized [27].

In this paper we first deal with the evaluation of the various properties which are unique to multiple channel networks and their relation to network performance. Specifically, we address the question of optimal network design with respect to 1) the partitioning of the system bandwidth into subchannels, and 2) the question of the functional design of the nodes' channel interface units. That an optimal network design exists is easy to see: in spite of maximally improving the packet transmission time to propagation delay ratio, the infinitesimal partitioning of bandwidth defies intuition. For example, at low network loads most subchannels will be unused while the remaining subchannels will work only at a small fraction of the original speed. Thus, we expect the optimal number of subchannels to be bounded and be derived as a function of, at least, the system load. Secondly, with regard to the node's channel interface, the nodes should be connected to all subchannels in order to preserve the advantages of broadcast channel communication [2]. As a consequence more than one transmission may be directed to a node on different subchannels. In this case we must determine the
number of subchannels on which each node should be able to receive simultaneously. The multiplication of nodes' channel interface mechanism to allow concurrent operation, yields a more expensive communication interface device and becomes particularly unattractive as the number of subchannels increases. The optimal interface design should thus be chosen as the one having a minimal amount of functionality duplication for a required network performance.

In the next section of this paper we construct an analytic model of multi-channel networks based on collision avoidance protocols, the channel access mode found in most current and expected very high speed networks. In Section 3 the introduced model allows us to evaluate alternative network architectures for any combination of bandwidth partitioning and node interface design aspects. In Section 3 we also show that a close relation between the network performance and these two architectural aspects exists and we prove that an optimal bandwidth partitioning and an optimal interface design can be found which yield maximum bandwidth utilization and minimum average packet delay for a given network characterized by number of stations, total systems bandwidth and the packet transmission time to signal propagation delay ratio. In Section 4 we show that multiplication of the node interface receive mechanism can further increase the system bandwidth utilization. The conclusions of Section 5 close the paper.

2. MODEL

The network is defined by the number of nodes $N$, the channel bandwidth $B$ in bits/seconds and the channel end-to-end propagation delay $\tau$ seconds. Denote $b$ the channel division factor into equal subchannels, each of bandwidth $B/b$. Each node is connected to every subchannel. A node can be simultaneously receiving a packet on one subchannel at a time. If more than one packet is sent to a node simultaneously, a conflict occurs and the additional packets are rejected. We
term this phenomenon a "destination conflict". The effect of conflict at a destination node causes loss of the bandwidth which was dedicated to the transmission of packets rejected at the destination. Similarly, when two or more nodes attempt to access a subchannel simultaneously, a loss of bandwidth will occur due to packet collisions. We must, therefore, construct a conflict and collision free subchannel allocation for packet transmissions in systems where the channel end-to-end propagation delay to packet transmission time ratio is significant. In these systems collision sensing and detection mechanisms cease to be effective [8]. Moreover, at high speeds the penalty required to scan all the subchannels in order to decide on which to transmit can also be most significant [1,3,19]. Therefore, we assume a family of collision free synchronous protocols with time axis divided into equal slots of length $s$. At the beginning of each slot we choose a maximum number (up to $b$) of packets under the conflict free constraint. We assume that the choice of suitable packets is executed prior to each slot avoiding the extra scan time needed to switch from one subchannel to another for finding an idle subchannel to transmit on. The scanning penalty free behaviour is representative of systems which execute scheduling per each slot on a separate reservation subchannel or which use an a priori assignment of transmission rights [15,23,24].

In the presented model data packets are assumed to be of constant length of $z$ bits. We denote $T_o$ to be the packet transmission time

$$T_o = \frac{z}{B}.$$  

Let $a$ be the normalized propagation delay with respect to $T_o$,

$$a = \frac{\tau}{T_o}.$$  \hspace{1cm} (1)

Let $T_b$ represent the packet transmission time on each subchannel. Then, the packet transmission time normalized with respect to $T_o$ is given by $b$. 

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We define the slot duration, $s$, of the system normalized with respect to $T_o$ as:

$$s = b + a.$$  

To model the packet generation process we assume that each node has one output buffer. Packet arrival to an empty buffer of each node is a Poisson process with mean arrival rate of $\lambda$ packets/packet transmission time - $T_o$, or $\lambda'$ packet/slot where

$$\lambda' = \lambda(b + a).$$  

Therefore the node packet generation is a Bernoulli process with rate $p = 1 - e^{-\lambda'}$ per slot.

The previous assumptions lead us to the formulation of a closed system model in which generation of packets occurs only when the node's transmission buffer is empty. This model has been shown to closely represent the communication activity in very high speed networks [16,18,19,27].
3. ANALYSIS

To evaluate the system performance we compute the average system throughput, the average packet delay and the system capacity. Under previous assumptions we can model the system by a discrete time Markov chain, obtained by observing the state of the system at the beginning of a slot. In the exact chain the states must record complete information about the distribution of the destinations of all packets in the system. Therefore, the number of states in the exact chain is explosive, leading to a very complex solution. To significantly reduce the model complexity, we construct an approximate Markovian model in which the state is represented by the total number of packets at the beginning of a slot. Assuming that a packet is directed to any destination node with equal probability we evaluate the state transition rates without the knowledge of the number of packets queued for each destination. We make use of the independence assumption: i.e., we assume that at the beginning of a slot each queued packet assumes a new destination equiprobably and independently [25].

Let $p_i$ represent the state probability, i.e., the probability that at the beginning of a slot there are $i$ packets in the system. Define $\lambda^*$ the rate at which packets cycle through the queueing network

$$\lambda^* = \left[ N - \sum_{i=0}^{N} i p_i \right] \cdot p$$

We define $S$ - the normalized throughput of the system, as

$$S = \frac{\lambda^*}{S}.$$  

Applying Little's result we obtain the average packet delay $D$, normalized with respect to $T_o$:

$$D = \frac{L}{S}.$$
where \( L \) is the average number of packets in the system. The average packet delay results from contending for the channel with other nodes, from contention created by destination conflicts and from the packet transmission time. To obtain the average packet delay we first compute \( L \), similarly to [27], as follows:

\[
L = \sum_{j=0}^{N} j p_j + \frac{1}{s} \int_{0}^{s} E(X_t) dt
\]  

(7)

Eq. (7) represents the expected number of packets at the beginning of the slot plus the expected number of packet arrivals - \( X_t \), during a slot \( s \). Given \( X_t \sim Bin((N-j),(1-e^{-\lambda t})) \) we obtain:

\[
E(X_t) = \sum_{j=0}^{N} p_j E(X_t \mid X_0 = j) =
\]

\[
= \sum_{j=0}^{N} p_j \sum_{i=0}^{N-j} i \binom{N-j}{i} (1-e^{-\lambda t})^{N-j-i} (e^{-\lambda t})^i
\]

\[
= \sum_{i=0}^{N-j} i \binom{N-j}{i} (1-e^{-\lambda t})^{N-j-i} (e^{-\lambda t})^i
\]

Substitution of (8) into (7) gives:

\[
L = \sum_{j=1}^{N} j p_j + \frac{1}{s} \left[ N - \sum_{j=1}^{N} j p_j \right] \left[ s - \frac{1}{\lambda} \left( 1 - e^{-\lambda s} \right) \right] = N \left[ \frac{1}{s} - \sum_{j=1}^{N} j p_j \right] (1-e^{-\lambda s})
\]  

(9)

and by substituting (9) in (6) we obtain

\[
D = \frac{N}{S} - \frac{1}{\lambda}.
\]  

(10)

To compute \( D \) and \( S \) we next find the state probabilities \( p_i \). Let \( \pi_{i,j} \) be the probability of exactly \( i \) packets originating in a slot from a binomial process with rate \( p \), given that at the beginning of the slot there are \( j \) packets in the system:

\[
\pi_{i,j} = \binom{N-j}{i} p^i (1-p)^{N-i-j}
\]  

(11)

Assuming synchronous system operation, see Section 2, we can choose up to \( b \) suitable packets for conflict free transmission at the beginning of each slot. We, therefore, compute the probability \( Q_j \) of finding exactly \( j \) packets (\( j \leq b \)) with
different destinations, given there are $i$ packets in the system ($i \geq j$). To find $Q_{ij}$ we consider the Bose-Einstein (B-E) system model [26]. We observe $i$ indistinguishable balls (packets) assigned with equal probabilities to $N$ distinguishable urns (destination nodes). We observe that given the assignment of $i$ balls to $N$ urns, $Q_{ij}$ will correspond to the probability of finding exactly $j$ balls, each belonging to a different urn. This probability is equivalent to the probability that there are exactly $N-j$ empty urns, given $i$ balls and $N$ urns.

Let $M_b$ denote the number of empty urns and $N_k$ the number of balls in the $k$-th urn ($k = 1, \ldots, N$). Then $Q_{ij}$ becomes:

$$Q_{ij} = \Pr[M_b = N-j \mid i, N] = \left[ \frac{N}{N-j} \right] \sum_{r=1}^{N-j} (-1)^r \left[ \frac{N-j}{r} \right] \Pr[\bigcap_{k=1}^{j} (N_k > 0) \mid i, N]$$

Equation (12) is obtained by noticing that the event $M_b = N-j$ occurs if exactly $j$ events of $N_k > 0$ occur, and by applying the inclusion-exclusion principle [26]. To compute this probability we notice that the total number of distinguishable arrangements in the chosen B-E system model is given by $\frac{i+N-1}{N-1}$. Therefore, the probability that exactly $j$ specified urns contain at least one ball is given by:

$$\Pr[\bigcap_{k=1}^{j} (N_k > 0) \mid i, N] = \frac{\binom{N+i-j-1}{N-1}}{\binom{i+N-1}{N-1}}.$$  

Substituting (13) in (12) we finally obtain:

$$Q_{ij} = \frac{\left[ \frac{N}{N-j} \right]}{\binom{i+N-1}{N-1}} \sum_{r=1}^{N-j} (-1)^r \left[ \frac{N-j}{r} \right] \binom{N+i-j-(j-r)-1}{N-1}$$

We now define $R_{ij}$ the probability that among $i$ packets in the system there are exactly $j$ packets whose transmissions can be carried out successfully given there are $b$ subchannels in the system:
We establish the following set of state equations assuming the system has reached equilibrium:

\[
\begin{align*}
    \mathbf{R}_0 &= \begin{cases} 
        \mathbf{q}_j & j < b \\
        \mathbf{1} - \sum_{k=1}^{b-1} \mathbf{q}_k & j = b 
    \end{cases} \\

\end{align*}
\]  

(15)

Due to multiple dependence of the various states, the set of state probabilities \( p_i \)'s is solved from the set of linear equations (16). Substituting the computed state probabilities into eq. (5) we obtain the throughput \( S \) and consequently the average packet delay \( D \).

To evaluate the effect of channel partition on the system bandwidth utilization, we first compute the maximum throughput \( S_{\text{max}}(b) \), defined as the system throughput obtained for a given \( b \), under heavy load, (i.e., \( p=1 \)), when no conflicts occur. With these assumptions, eq. (5) becomes:

\[
S_{\text{max}}(b) = \frac{1}{1 + \frac{a}{b}}. 
\]

(17)

We define the system capacity \( C \) as the \( \max_b S_{\text{max}}(b) \) obtained over all possible values of the channel partitioning factor \( b \). Clearly, the capacity is obtained when
the number of subchannels equals to the number of packets in the system at the
beginning of each slot. Since in the considered model we choose a constant value
of $b$, the maximum throughput will be obtained when also the number of packets
at the beginning of each slot remains the same. Given the closed queueing model
and the preceding observations, the capacity is obtained when the number of
active nodes equals to the number of blocked nodes (nodes having packets
buffered for transmission in the current slot). This number equals to $\lfloor N/2 \rfloor$ yielding also $b = \lfloor N/2 \rfloor$. The substitution of $b = \lfloor N/2 \rfloor$ into eq. (17) produces the system
capacity:

$$C = \frac{1}{1 + \frac{a}{\lfloor N/2 \rfloor}}$$

(18)

3.1 Results

As suggested from the preceding analysis and as clearly seen from eq. (17)
the multichannel system performance depends heavily on the normalized propa-
gation delay $\alpha$ and the number of nodes $N$.

Figure 1 shows the relation between system capacity $C$, and the normalized
propagation delay $\alpha$, for varying number of nodes $N$. We observe that without
bandwidth partitioning, i.e. taking $b=1$, the system capacity quickly deteriorates
as $\alpha$ increases. Notice that in this case the capacity $C$ simply becomes equal to
the classic capacity definition given for multiple access channels by, $C = \frac{1}{1+\alpha}$
[2,8,22,23]. By partitioning the bandwidth, $b > 1$, improvement in capacity can be
obtained for every $N$ as seen from eq. (18). The capacity improvement increases
as $N$ grows, since larger $N$'s allow the use of a higher partitioning factor
$b = \lfloor N/2 \rfloor$. Thus with every subchannel that can be fully utilized the ratio between
packet transmission time and the propagation delay increases leading to better
utilization of the total system bandwidth.

At lower loads \( p < 1 \), no all \([N/2]\) subchannels can be fully utilized, while the utilized subchannels work at lower speed. This leads to lower system throughput and higher packet delays when \( b = [N/2] \) is taken. Thus for lower loads the best performance is obtained for a partitioning factor \( b \) which is strictly less than \([N/2]\). These effects are reflected in figures 2 and 3. Figure 2 shows the throughput \( S \) as a function of arrival rate \( \lambda \) packets/packet, transmission time \( T_0 \), for \( N=8 \) and \( \alpha=1 \). We see that below \( \lambda=0.05 \) the single channel system \((b=1)\) gives the best performance. For traffic loads between 0.05 and 0.28 maximum throughput is achieved for \( b=2 \) and for loads beyond 0.28 maximum throughput is achieved for \( b=3 \). Thus, as suggested earlier, for different traffic loads different values of \( b \) provide the best performance. Figure 3 shows the system throughput versus node arrival rate for the same network with higher normalized propagation delay \( \alpha=5 \). We see that for corresponding \( \lambda \) values, when the normalized propagation delay \( \alpha \) increases from 1 to 5 additional channel partitioning leads to better system throughput. This observation is consistent with the intuition obtained from figures 1 and 2 suggesting that from considerations of improving the \( \alpha/b \) ratio higher \( \alpha \) values require a higher channel partitioning factor. Similar observations hold for the average packet delay \( D \) versus throughput \( S \) system performance shown in figure 4.

An important point to be noticed from figures 2 to 4 is that at very high loads not only is the capacity not reached but also the maximum throughput \( S_{\text{max}}(b) \) \((b < [N/2])\) are not obtained. The explanation for this behaviour is the existence of the destination conflict shown in eq. (14) which prevents the additional sub-channels from being utilized even at high loads due to the non-existence of suitable packets among the packets present in the system. This conflict should be most pronounced for small number of nodes. We therefore next observe the throughput, for very high loads, as a function of \( N \) the number of network nodes.
Figure 5 shows the system throughput as a function of the number of nodes $N$ for different partitioning factors with $a=1$. We observe that the throughput is an increasing function of $N$. This is due to the ability to utilize a higher number of subchannels as $N$ increases, thus improving the $a/b$ ratio in the system. On the other hand, notice that for a given $b$ value the maximum throughput $S_{\text{max}}(b)$ is obtained only when the number of nodes $N$ is high enough to occupy all subchannels. Notice also that this $N$ value is larger than $2b!$, see eq. (15). Thus, for example, for $b=2$ $S_{\text{max}}(2)$ is obtained only for $N \geq 11$ and for $b=4$, $S_{\text{max}}(4)$ is obtained for $N \geq 15$, while for $N=4$ and $8$ respectively, the highest obtainable throughput is significantly smaller than $S_{\text{max}}(b)$. Thus, we can conclude that the system is not able to utilize $\lfloor b/2 \rfloor$, the optimal number of subchannels. This behaviour most clearly demonstrates the performance degradation due to destination conflicts.

3.2 Optimization

As seen from the previous section a single channel division factor $b$ exists which provides the best system performance for a given system configuration $(a,N,\lambda)$. We denote this optimal channel partitioning factor by $b^*$. 

**Theorem:** The channel division $b^*$ that maximizes the throughput $S$, simultaneously minimizes the average packet delay $D$.

**Proof:** Immediate from equation (10).

**Corollary:** It is sufficient to optimize one of the performance measures.

For maximizing the throughput for a given system configuration $(a,N,\lambda)$ we construct the following algorithm:

$$S = 0; \text{ found } = \text{ False};$$

for $b := 1$ to $\lfloor N/2 \rfloor$ while not found;
begin:
  solve the set of equation (16) for obtaining $p_i$'s
  
  \[ S_{\text{MAX}} := (N - \sum_{i=1}^{K} p_i) \left(1 - e^{-\lambda(b+n)}\right) / (b + n) \]
  
  if $S_{\text{MAX}} < S$ found:=True
  
  $S := S_{\text{MAX}}$
end:

The algorithm terminates at $b = b^\ast$.

4. CONFLICT ELIMINATION BY MULTIPLYING THE NODES' CHANNEL INTERFACE RECEIVE MECHANISM

The preceding optimization procedure enables us to maximize throughput by selecting an optimal $b^\ast$ value. However, as shown in the previous section, due to destination conflicts the best performance may be obtained for $b^\ast < \lfloor N/2 \rfloor$, thus yielding a maximum throughput smaller than $C$. Therefore we see that for a given configuration $(a, N, \lambda)$ further increase in bandwidth utilization can be only achieved by eliminating this conflict. In this section we propose destination conflict elimination by the multiplication of the node's receive mechanism. To evaluate this "extended" system performance, we generalize the network model presented in Section 2, and construct an appropriate performance model. We use this model to demonstrate the extent of improvement resulting from the node's interface functionality multiplication.

4.1 Performance Evaluation of Multiple- Receivers/Multiple- Channels System

In addition to the assumptions introduced in the preceding model we assume that each node's channel interface is able to receive on $k$, $1 \leq k \leq b$ subchannels simultaneously. We now redefine the destination conflict as the phenomenon in
which \( n, n > k \) packets are being sent to a node simultaneously. In this case, all \( n-k \) additional packet will be rejected.

In order to evaluate the system behaviour with \( 1 \leq k \leq b \) we must first redefine \( Q_n \) to be a function of \( k \). We denote the \( k \)-dependent probability by \( Q_n(k) \). Using the allegory introduced in Section 3, we see that given the assignment of \( i \) balls to \( N \) urns, \( Q_n(k) \) corresponds to the probability of finding exactly \( j \) balls in such a way that no more than \( k \) balls belong to the same urn. We denote by \( l \) the number of urns containing at most \( k \) balls. Clearly, \( (N-l) \) urns will contain at least \( k+1 \) balls.

Consider the construction shown in Figure 8. This construction represents the distribution of \( i \) balls, out of which exactly \( j \) suitable balls are chosen, given there are \( l \) urns containing at most \( k \) balls. The number of ways we can distribute \( i \) balls, as shown in Figure 6, is given by

\[
\sum_{l=N-i}^{N-1} \binom{N}{l} \cdot A_{k-l} \cdot \sum_{m=0}^{k} M_m = l, j - (N-l) \cdot k
\]

(8)

where, \( A_{n,m} \) is the number of distinguishable arrangements of \( n \) (indistinguishable) balls in \( m \) urns, and \( \sum_{m=0}^{k} M_m = l, j - (N-l) \cdot k \) is the number of distinguishable arrangements of \( j - (N-l) \cdot k \) balls in \( l \) urns in such a way that all the \( l \) urns contain at most \( k \) balls.

\[
\left[ \sum_{m=0}^{k} M_m = l | j, a \right] = \sum_{m=0}^{l} (-1)^m \binom{l}{m} \left[ \bigcap_{r=1}^{m} (N_r > k) | j, a \right]
\]

(9)

The computation of eq. (9) is obtained by observing that \( \sum_{m=1}^{k} M_m = l \) if no event of \( (N_r > k) \) occurs, i.e.

\[
\left[ \bigcap_{r=1}^{m} (N_r > k) | j, a \right] = 1 \cdot A_{a-m(k+1)}, l
\]

(10)
i.e., \( m(k+1) \) (indistinguishable) balls are distributed in the first \( (k+1) \) places of \( j \) urns and the remaining \( (a-m(k+1)) \) balls are distributed in \( A_j \) distinguishable arrangements. Substituting (10) in (9) and using the inclusion-exclusion principle we obtain:

\[
\left[ \sum_{m=0}^{\ell} M_m = l \right] = \sum_{m=0}^{\ell} (-1)^m \frac{\binom{l}{m}}{(l-1)} \left[ l + a - m(k+1) - 1 \right]
\]

Substituting (11) into (8) and noticing that the total number of distinguishable arrangements is \( \binom{l+N-1}{N-1} \) we obtain the probability \( Q_j(k) \) as follows:

\[
Q_j(k) = \frac{1}{\binom{l+N-1}{N-1}} \cdot \sum_{i=N}^{N} \frac{\binom{N}{l}}{\binom{l}{i}} \left[ \frac{N-l+i-j-N+l-1}{i} \right]
\]

\[
\cdot \sum_{m=0}^{\ell} (-1)^m \frac{\binom{l}{m}}{(l-1)} \left[ l + (j-(N-l)k)-m(k+1) - 1 \right]
\]

Note: \( \binom{A}{B} = 0 \) if \( B < 0 \) or \( B > A \).

For computation of the system throughput \( S \), and the average packet delay \( D \) in the generalized network model we substitute \( Q_j(k) \) instead of \( Q_j \).
4.2 Results

Using the introduced analytic model, we evaluate the potential gain in throughput which results from the ability of each station to receive packets on \( k \) subchannels in each slot. Owing to the use of an approximate model dictated by the complexity of an exact solution \([27]\) simulation results are also included for validation purposes. Figure 7 presents the throughputs vs. load behaviour for a network model identical to the one given in figure 2. In Section 3 we learned that system capacity can not be reached due to destination conflicts. In figure 7 we evaluate the system behaviour for the \( b=\lfloor N/2 \rfloor \) factor division as a function of \( k \). We expect that as \( k \) increases the probability of destination conflict is reduced and so the number of utilizable subchannels will be increased. Figure 7 shows that consistent with these observations, for every load value, the throughput is an increasing function of \( k \). This increase becomes more pronounced as the network load increases since with low loads the probability of destination conflict is small anyhow due to the small number of queued packets. Secondly, for any given load, the marginal throughput benefit obtained by progressive increase in \( k \) decreases, as \( k \) increases. This results from the fact that the probability of having \( i \) packets \( i > k \) destined to a single node is a non linearly decreasing function of \( k \). This behaviour is observable also from analyzing the behaviour of the \( Q_j(k) \) function. Thus for example in the given system of \( N=8 \) the probability of finding more than three packets with the same destination in one slot is negligible. In fact, for sufficiently high loads, the throughput behaviour approaches the system capacity given by eq. (17) already for \( k \geq 3 \).

The ability to receive several packets simultaneously also leads to reduced average packet delay. Figure 8 compares the performance obtained by taking \( b=1,\ldots,\lfloor N/2 \rfloor \), and \( k=b \) to the performance of a similar network model given in figure 4. We again see that at high throughput values larger \( k \)'s \((k=b)\) can, due to virtual elimination of destination conflicts, significantly reduce the expected
packet delay.

In conclusion therefore the proper choice of the $b$ and $k$ system parameters can be introduced to optimize the total system behaviour, given as a function of $N$ and $a$, to simultaneously maximize bandwidth utilization and minimize the average packet delay. This optimization can be targeted towards a given expected system load $\lambda$, e.g. to obtain maximum throughput at high loads, or can be executed continuously adapting these parameters as a function of the load in future communication systems [7].

5. CONCLUSIONS

This paper has presented a communication model of broadcast bus based very high speed networks. It was demonstrated that in these systems the ratio between the packet transmission time and the time needed for the packet to propagate through the system has a dominating effect on the communication systems' utilization, the channel throughput and the average packet delay. In order to improve the system performance an architectural approach was presented in which several subchannels are used in parallel. The introduced analytic model showed that such channel configuration has the potential to significantly improve the network performance. Furthermore it was shown that for a given network configuration expressed in terms of the number of nodes, node arrival rate and normalized propagation delay an optimal channel partitioning can be found. This optimal partitioning simultaneously maximizes network throughput and minimizes the average packet delay.

Lastly, it was shown that the ability to utilize a multichannel system bandwidth is dependent on the node's channel interface functionality. This dependence was shown to be particularly significant for networks with small number of stations. As a result an increase in the nodes' interface capability which enables
each node to simultaneously receive packets on several subchannels was introduced and it was demonstrated that in this way the limitation on the utilization of bandwidth in multichannel architecture based systems can be removed.
Figure 1 - System capacity versus normalized propagation delay.
Figure 2 - Throughput versus node arrival rate for $N=8$ and $a=1$. 

Throughput, $S$ vs. Node arrival rate, $\lambda$: 
- $b=5$ 
- $b=4$ 
- $b=2$ 
- $b=1$ 

Simulation points: o
Figure 3 - Throughput versus node arrival rate for $N=8$ and $a=5$. 

Throughput, $S$

Node arrival rate, $\lambda$
Figure 4 - Average packet delay versus throughput for $N=8$ and $a=1$. 
Figure 5 - Throughput versus number of nodes for $p=1$ and $a=1$. 

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The table represents a construction of $Q_{ij}(k)$ computation.

<table>
<thead>
<tr>
<th>N</th>
<th>$i-j-N+k$ balls</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\vdots$</td>
<td>$\vdots$</td>
</tr>
<tr>
<td>$k+1$</td>
<td>$(N-k)\cdot k$ balls</td>
</tr>
<tr>
<td>$k$</td>
<td>$\vdots$</td>
</tr>
<tr>
<td>$\vdots$</td>
<td>$\vdots$</td>
</tr>
<tr>
<td>$1$</td>
<td>$(N-k)\cdot k$ balls</td>
</tr>
</tbody>
</table>

- $i$ urns, $N-k$ urns
- At most $k$ balls, at least $k+1$ balls

**Figure 6** - Construction of $Q_{ij}(k)$ computation.
Figure 7 - Throughput versus node arrival rate for $N=8$, $a=1$, and $b=4$
Figure 8 - Average packet delay versus throughput for N=8 and a=1.
REFERENCES


