In this paper we investigate the performance characteristics of multihop homogeneous S-ALOHA-type packet radio networks. Special attention is paid to the second layer station protocols that include channel access, acknowledgment scheme and buffer management. We develop an analytic queuing network model assuming limited queue dependency. We also accept multiple copies of global acks piggybacked to data packets and a window mechanism for transmission control purposes. We investigate the influence of the window size on the station throughput and the average packet delay. The theoretical network performance parameters are obtained by the steady-state analysis of an isolation buffer. The simulation results are evaluated by the use of regenerative simulation method. The results demonstrate that an increase of the window size significantly improves the efficiency of station operation.

1. INTRODUCTION AND GENERAL ASSUMPTIONS

In the paper we develop analytic and simulation models of multihop S-ALOHA packet radio networks with regular structures. We model the packet radio network as a network of queues. Since the various station interactions make such a model very complex we investigate the behaviour of networks using an approximate model. In particular, we assume limited queue dependency [2]. We restrict our considerations to regular networks, analysing the behaviour of one station only. We are especially interested in the second layer station protocols [3], that include channel access, acknowledgment scheme and buffer management. We make use of a discrete-time Markov chain approach [4]. We use the S-ALOHA technique for channel accessing. As this technique is used for data transmission, it is necessary to provide highly reliable control. This can be accomplished by transmitting an acknowledgment packet for each successfully received data packet. This mechanism introduces extra traffic, causing a serious degradation of the network performance parameters [5], [6]. In most papers, it has been assumed that the control traffic is transmitted over a separate control channel so as not to use any capacity of the data channel. In this paper we assume that acks and data packets share the same communication medium. In contrast to [5], [6] we accept that acks are always sent back to source stations attached to data packets (piggyback). From the analysis of S-ALOHA channels it follows that the loss of an ack due to a collision has a strong impact on the network performance. Such an event requires not only the retransmission of the ack, but also, what is much more important, the retransmission of the data packet, possibly more than once. This suggests [6] that the transmission of several copies of an ack for the same data packet may improve the network operation. In accordance with this we assume that acks pertaining to the same data packet are attached to all packets sent to a source station within a given time T.

From the literature we know that the selective ARQ schemes of the continuous transmission type are reliable error control techniques used in point-to-point links. In this paper we investigate the usefulness of an ARQ method with the window mechanism, whereby packets are transmitted in succession without waiting for receipt of previous transmission. The only difference as compared to the selective ARQ scheme is that in our model we always advance the window by one when an ack comes in (even when it does not fit to the lower edge of the window). Only packets not acknowledged within the time-out T (t≤T) are required to be retransmitted. To arrange such ARQ system it is necessary to equip stations with buffers assigned to local or transit data packets and their copies. The capacity of a buffer of packet copies corresponds with the window size. Since acks are sent back to source stations piggybacked to data packets only, their intensity clearly depends on the output rate of data packets from a station, that can be relatively low. Thus, in the following we assume that each ack carries out the global acknowledgment of all data packets correctly received from a given station within time T.

In the model developed in the paper, in contrast to some previous works (e.g., [7]), we assume that all stations not only generate and receive packets but also relay any packets in transit. Furthermore, we assume that at any time a station can be either transmitting or receiving, but not both simultaneously.

In the following we first develop a general network model. Then we evaluate some station performance measures applying the Markov chain approach or the regenerative simulation method [8]. The primary performance measure is the station throughput. Others include the average packet delay and the average numbers of packets in the station buffers. We investigate the influence of the window size on the main station performance measures.

2. STATION MODEL

We consider regular networks that consist of a certain number M of homogeneous stations. The stations are able to communicate directly only with m (m<M) neighboring stations located within their hearing range. All stations are identical, in particular, equipped with five buffers as shown in Fig. 1. Four of them are assigned to local and transit packets (BLP and BTP, respectively) and their copies (buffers BCLP and BCTP, respectively). The fifth buffer is assigned to acks awaiting transmission of data packets to appropriate adjacent stations. Notice that...
values for packets in buffers BCLP and BCTP means that two time-outs can never occur simultaneously. Hence
\[ \Pr(\text{no time-out in BCTP and no time-out in BCLP}) = \Pr(t_{\text{cl}}) \times \Pr(t_{\text{ct}}) = 1 - \frac{1}{1/P_{K}} \times (1 - g)^m \]  
\[ \text{(2)} \]
In the above formula, \( t \) denotes a time-out event while the \( t \) the lack of a time-out.

Without loss of generality and for the sake of simplicity we shall assume that time-out intervals \( t \) slightly differ in different neighbouring station. This is necessary to avoid permanent packet interferences.

A data packet is always directed to only one of the \( m \) neighbouring stations of a source station. A successful packet reception by a single-hop destination station requires:

(i) - no interference with packets possibly sent by the \( m-1 \) other neighbouring stations of the receiving one and no transmission from the receiving one
\[ p = (1-g)^m \]  
\[ \text{(3)} \]
(ii) - no rejection from BTP due to overflow, if the data packet is transmit a one
\[ \Pr(\text{successful packet reception}) = (1-g)^m \]  
\[ \text{(4)} \]
where \( I \) - the average number of transmission hops in the network, \( g \) - the probability that buffer BTP is full.

Notice, however, that for packets for which one of the \( m \) adjacent stations is a destination one only condition (i) must be satisfied.

To find the throughput components \( g_{i_{1},i_{2}} \), \( i_{1} = 1,2 \) we must determine the traffic components \( g_{i_{1},i_{2},i_{3},i_{4}} \), the probability of ack reception and the probability of packet successful reception. For this purpose we must analyse the buffers shown in Fig. 1.

The key element in our analytic station model is buffer BCTP, served with the highest priority. The capacity of this buffer, \( K \), accounts for the window size for transit packets. Notice, too, that buffers BCTP and BCLP are not served in FIFO order, as the order of ack arrivals may differ from that which the corresponding data packet are transmitted. To analyse the behaviour of this buffer we consider the state transition diagram depicted in Fig. 2. The states of buffer BCTP are described by the number of packets, \( k \), in this buffer, just prior to the start of the next time slot. Any state \( k \), except \( k=0 \), is split into two substates \( k' \) and \( k'' \). Retransmissions caused by time-out take place only in substates \( k'' \). One can observe a close analogy between such buffer behaviour and that of a bulk service system with bulks of a random size. In our case acks attached to data packets can carry information about several data packets successfully transmitted between two adjacent stations within a certain period \( T \). The transition probabilities \( a(k,k-1), k=1,2,..,K \), \( k=1,2,..,K \) corresponding to an acknowledgment of \( l \) data packets depend on the BCTP state, \( k \). The transmission rates from buffer BTP, \( g_{i_{1}}(k) \) are also dependent on these states. Thus the
probability of time-out in buffer BCTP (the event corresponding to a packet retransmission) that is equivalent to the probability of remaining in substate \( k^{*} \), clearly depends on the number of packets in buffer BCTP.

Let us assume the existence of steady-state conditions in buffers at a station. To obtain general formulae for the probabilities of states of buffer BCTP, \( P_{k} \), \( k=0,1,2,\ldots,K \), it is necessary to solve the following equations:

\[
P_{k} = \sum_{l=0}^{K} P_{l} a(1,0) + \sum_{l=1}^{K} P_{l} g_{l}(k-l)
\]

Next, taking into account that \( P_{k} = P_{k+1} \), we get the probability of time-out in state \( k \) as

\[
P_{k} = \Pr(t_{cl} \leq k) = \frac{\sum_{l=k+1}^{K} P_{l}}{1+b(k)-c(k)}
\]

To calculate the average probability of time out \( \Pr(t_{cl}) \), which is equal to \( g^{*} \), we must find exact or approximate formulae for the transition probabilities shown in Fig. 2. First we consider the probabilities of ack arrivals, \( a(k,k-1) \). Next we evaluate the probability of entering substate \( k^{*} \), the probability of remaining in substate \( k^{*} \), \( c(k) \) and the probability of transition from \( k^{*} \) to \( k \), \( d(k) \).

Prior to our analysis we assume that:
- all the \( m \) neighbouring stations generate the same traffic \( g \) (per slot),
- the average traffic from a station to each of the \( m \) neighbouring stations is the same in all slots (regardless of actions taken in the past) and equals \( g^{*} = g/m \).

Packet copies can stay in buffer BCTP for random time intervals \( t_{c} \), \( R(0,1,2,\ldots) \), and \( t \in (0,t_{c}) \), while an ack's "memory" covers the last \( T \) slots (starting from the time instance when a packet was successfully received). This means that an ack for a successfully received packet is attached to all packets sent to an appropriate station within \( T \) slots. After this time interval the ack counter is reset to zero i.e., a new successful transmission attempt for the packet is required. Assuming that \( p \) is the probability of successful packet reception (see (3)) we get the average number of packet transmission attempts terminated by a successful one as

\[
r = \frac{1}{1-(1-g)^{m}}
\]

Therefore we can accept that in a given time slot all packets stored in buffer BCTP were transmitted at least \( r \) times (where \( r = \lceil r \rceil \), denotes the smallest integer value greater or equal to \( r \)). Let \( T=nT_n \), \( n=1,2,\ldots \). For \( n=1 \), the length of the ack memory interval is equal to \( T \). Let us assume that in our case \( n=r \) and buffer BCTP is in state \( k \). Thus, the probability that any chosen packet from buffer BCTP was successfully received at least once in \( r \) attempts is

\[
P = 1 - (1-(1-g)^{m})^{r-1}
\]

Next, the probability that of \( k \) packets in buffer BCTP, \( i \) were sent without interference takes the form

\[
P(i/k) = \binom{m}{i} P^{i}(1-P)^{k-i}
\]

These \( i \) packets can possibly be directed to \( n \) destinations \( (n \geq m) \). Let \( i = i_1 + i_2 + \ldots + i_n \), where \( i_1 \geq 1, j=1,2,\ldots, n \) is the number of packets successfully sent to \( j \)-th of the \( n \) stations. Thus, the probability that the \( i \) packets transmitted without interference are directed to exactly \( n \) destinations is

\[
P(i/k) \binom{m}{i} \prod_{j=1}^{n} \frac{i_j!}{(i_j-1)!} \cdot \frac{(m-i)\ldots(1)}{i_1!\ldots i_n!} = \frac{a(k/i/i_1\ldots i_n)}{1+b(k)-c(k)}
\]

Assume, that \( 1 \) is the number of packets out of \( i \) that were directed to one of the \( n \) stations, while \( j \) the number of stations which successfully received \( 1 \) packet of the \( k \) stored in buffer BCTP. Hence, the transition in buffer BCTP from state \( k \) to \( k-1 \) requires a successful data packet transmission with the piggybacked ack from such a station. This event takes place with probability \( a(k,k-1) \)

\[
a(k,k-1) = \sum_{i=1}^{m} \sum_{j=1}^{i} \sum_{i'} \frac{a(k/i_{i_1}\ldots i_{i_n})}{1+b(k)-c(k)}
\]

In particular, the transition from state \( k \) to \( 0 \) is described by

\[
a(k,0) = a(k/0/k) = \frac{g^{*}(1-g)^{m}}{1+b(k)-c(k)}
\]
Now, let us consider the internal transitions between states $k$ and $k'$. The transition from $k$ to $k'$, corresponding to a time-out event in buffer BCTP occurs when:

- the unsuccessful packet transmission took place exactly $t$ slots earlier,
- there was either no data packet sent back to a station in question or no successful one after a given packet successful transmission, which took place exactly $t$ slots earlier.

This means that the probability $b(k)$ of transition to a state $k'$ (from state $k$) is as follows:

\[ b(k) = \sum_{i=0}^{K-k} \binom{K}{i} (1-p)^i p^{K-i} \cdot \left(1-g' \right)^m \]

Next, the probability of remaining in state $k'$ in the succeeding slot can be expressed as:

\[ c(k) = \begin{cases} b(k-1), & k=2, \ldots, K-1 \\ 0, & k=1 \end{cases} \]

Hence, the probability of transition from state $k'$ to state $k$ takes the form:

\[ d(k) = 1 - c(k) \]

To complete the analysis of the buffer BCTP it is necessary to evaluate the probabilities $g(k)$, $k=0,1,\ldots,K$. To obtain these probabilities we must analyse buffer BTP, which is served in FIFO order. It is evident that the behaviour of this buffer is strongly influenced by buffer BCTP states $k$ and capacity $K$.

Notice that at the same time this buffer behaviour can also be affected by packets stored in buffer BCLP. However, assuming the existence of equilibrium conditions and accepting that the intensity of local packets, $\lambda_1$, is very small ($\lambda_1 \ll \lambda$), we can analyse the state transition diagram shown in Fig. 3. In this diagram the arrival rate of transit packets, $\gamma_1$, is constant, i.e.,

\[ \gamma_1 \approx (\gamma_1') \cdot g' \cdot (1-g') \cdot (1 - \frac{1}{t}) \]

Fig. 3. A Markov chain model for buffer BTP

regardless of the output rates from a station in question. Assuming that the stationary conditions hold (9), viz., $g(k; K, \gamma_1, \nu_k) = 1, \nu_k < \nu$, and $K >> 1$, we get $g(k; K, \gamma_1) = \nu_k^{-k}$. We accept this approximate formula as the first order approximation of $g(k; K, \gamma_1)$. Using $\gamma_1$ as $\lambda_1$, we can calculate buffer BCTP state probabilities $P_k$ and the probabilities of time-out, $P_t$.

Finally, using (6) we obtain the average probability $g_{\text{p}}$ of packet retransmission from buffer BCTP. This completes the first step of the analysis. The next steps of our iterative algorithm include:

- repeated analysis of buffer BTP with the use of results obtained from buffer BCTP analysis (for $K_{\text{ct}} \to \infty$ and still accepting $\lambda_1 = 0$);
- this leads to new results for $g_k(K_{\text{ct}})$ and $g_{\text{p}}$.

A similar analysis applied to buffers BCLP and BLP, for $\lambda_1 > \lambda$ (the analysis of these buffers becomes very complex, since they are served with lower priorities).

To get more accurate results the above procedure should be repeated several times.

3. SIMULATION MODEL

In this paper we present simulation results obtained by the use of the regenerative simulation method (9). This type of simulation is recognised as a versatile and useful tool in performance evaluation of data communication systems. All performance parameters were derived on the basis of 60-100 simulation experiments i.e., regeneration cycles. In all cycles we started simulation experiments from the empty-and-idle conditions (regenerative points). We applied statistical tests with the confidence interval 95%.

The experiments were carried out for different sets of station parameters and network structures. Since we simulated all buffer functions in a chosen network station we limited our simulation experiments to rather simple network models only. The analysed networks correspond to the examples depicted in Fig. 4.

4. EXAMPLE RESULTS

In this section the performance measures of the considered model of a station are examined and compared. We analyse the parameters of a chosen station in terms of the maximum achievable station throughput and the expected packet delay, with respect to that station's local neighbourhood. We assume that all adjacent stations generate equal traffic $g$, which can be different from that generated by our station (i.e., $g + g$). Additionally we accept that $T_s$, which is the delay to an echo memory interval equals the time-out period. Further we assume that $t=80$ slots. We also assume that the buffer capacities are as follows: $K_1 = 0$ for buffer BLP, $K_{\text{ct}} = 0$ for buffer BCLP, whereas for buffer BTP and BCTP we assume that their total capacity $K = K_{\text{ct}} = 10$. In the following, the capacities assigned to these buffers are denoted by $(x; y) = (K_{\text{ct}}; K_{\text{ct}})$.

In Fig. 5/a and b we plot the station throughput components together with the traffic components versus the total traffic $G_{\text{mp}}$ offered by all neighbouring stations, for the network model shown in Fig. 4a. In Fig. 5a we also present analytic results for $g_k(K_{\text{ct}})$ and $g_{\text{p}}$ obtained for $\lambda_1 = 0$ and $K_{\text{ct}} = K_{\text{ct}} = (1,0)$. One can see a very good match of the analytic and simulation results. Fig. 5b shows the comparison of the station throughput components with respect to the traffic $G$. The results...
demonstrate that the throughput depends very strongly on the capacities of buffers BTP and BCTP.

It is no surprise that the maximum values of \( s \) (\( s_i \)) are achieved for bigger values of \( K \). The simple explanation is that for relatively small \( K \) and for high traffic rates, buffer BCTP is very often full. Thus no progress in transit packets transmission can be made.

In Figure 6a we plot the expected delays for transit, \( D_t \), and local packets, \( D_l \), versus the offered traffic \( G \). For \((K, K_{cl}) = (1,9)\) much smaller delays for transit packets are observed, while for \((K, K_{cl}) = (9,1)\) the situation is completely different. In both cases the minimum values of \( D \) are obtained for the values \( G \) from the interval \((0.5,0.6)\). This is caused by two factors, namely, by the small ack rates at \( G < 0.5 \) and high probabilities of packet interferences at \( G > 0.6 \). Packet delay variations versus the total station traffic \( s \) are presented in Fig. 6b. Once again the best station performance, from the transit packets point of view, is recognized when \( K_{cl} = 9 \).

We have presented an analytic queuing network model of an S-ALOHA-type packet radio network with multi-ack copies and a window mechanism. The theoretical results were obtained by means of steady-state analysis of some Markov chains, and subsequently verified using the regenerative simulation method. The results reveal that in network where acks (single or global) are carried by data packets only, an increase of the window size, which entails increasing the capacities of the buffer of copies, improves the efficiency of station operation.

**REFERENCES**


