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Title : **PERFORMANCE ANALYSIS OF THE CIRCUIT RESERVATION MULTIPLE ACCESS PROTOCOL FOR WIRELESS OFFICE COMMUNICATIONS.**

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In this report the new Circuit Reservation Multiple Access protocol for wireless office communications is presented. This slotted protocol controls the transport of data between a central base station and users with divergent service requirements over a half duplex radio link. An analytical and a simulation model are presented and the results of these models are evaluated for the performance analysis of the protocol.

Indexing terms : Cellular packet communications, Circuit Reservation Multiple Access, Integrated voice/data protocol and Wireless office communications.

SUMMARY.

To realise flexibility in the placement of communicating equipment in an office environment, a wireless communication system is the most appropriate way. To be prepared for the future, this wireless network has to deliver an efficient integrated transport facility for a lot of different electronic services.

A new Circuit Reservation Multiple Access (CRMA) protocol is presented in this report, which controls the integrated data transport over a half duplex radio link. Terminals with divergent service requirements and a group base station, all located in a small geographical area, transport their data over a common radio channel. Communication between base stations of different groups is possible over a high speed backbone network.

CRMA fulfils both the real time requirements for the circuit switched services and the low loss demands for random access applications.

In this study the throughput and delay characteristics of the CRMA protocol for the integration of speech and data traffic are considered.

The results of the analytical and the simulation model, which have been built in this research for the performance analysis of the CRMA protocol, match perfectly.

A cellular structure with cell sizes up to 300 m is considered. Each cell with a maximum of 20 speech and 20 data users. With this population CRMA appears to deliver a stable channel, without the necessity of load control.
The performance of the protocol can be optimised by adjusting the retransmission probabilities for the data terminals and the base station.

For the speech users the allocated bandwidth is guaranteed. The data users share the capacity left unused by the speech users. The maximum utilisation of this remaining capacity can vary between 37% and 60%, depending on the direction of the main traffic stream, towards respectively from the base station.

LIST OF SYMBOLS AND ABBREVIATIONS.

a	:	Worst case propagation delay.
BACK	:	DBO terminal(s) or GBS backlogged.
bin()	:	The binomial probability function.
CBO	:	Continuous Bitstream Oriented.
CBO_{circ}	:	Average number of necessary CBO circuits.
CBO_{sl}	:	Number of slots assigned to CBO traffic.
cbothr	:	The fraction of the link capacity assigned for the transportation of CBO data.
CONN SLNT	:	State of CBO terminal, which indicates it has been assigned a connection and is in a silent period.
CONN TALK	:	State of CBO terminal, which indicates it has been assigned a connection and is in a talking period.
CRMA	:	Circuit Reservation Multiple Access.
CTR	:	CONTROL data.
CTR_{sl}	:	Number of CONTROL slots in each frame.
DBO	:	Discontinuous Bitstream Oriented.
decr(y)	:	Function which decrements value of y with one.
GBS	:	Group Base Station.
inb_outb	:	Ratio between inbound (produced by DBO terminals) and outbound (produced by GBS) DBO packet arrival rates.
incr(y)	:	Function which increments value of y with one.
$J\ (m,\lambda_c)$	:	The reciprocal value of the blocking probability for m sources, with a call arrival intensity per free source of λ_c.
k	:	Maximum number of CBO circuits per link.
m	:	Number of CBO users in the group.
MCMA	:	Minipacket Competition Multiple Access.
n	:	Number of DBO users in the group.
NO CONN	:	State of CBO terminal, which indicates it has not been assigned a connection.
nr_{CBO}	:	Number of CBO terminals.
nr_{DBO}	:	Number of DBO terminals.
nr_ncon	:	Number of CBO terminals which are in the state "NO CONNECTION" at the beginning of a CBO traffic simulation run.

nr_slnt	:	Number of CBO terminals which are in the state "CONNECTION SILENT" at the beginning of a CBO traffic simulation run.
$nr_{rtr\ DBO}$	:	Average number of retransmissions done by a DBO terminal.
$nr_{rtr\ GBS}$	:	Average number of retransmissions done by GBS.
nr_talk	:	Number of CBO terminals which are in the state "CONNECTION TALKING" at the beginning of a CBO traffic simulation run.
OCC	:	Occupied.
ORIG	:	DBO terminal(s) or GBS in originating mode.
p	:	Chance of a packet arrival at a DBO station, in one slot period.
p1	:	Probability that a free CBO terminal initiates a call.
p2	:	Probability that a calling CBO terminal terminates its call.
p3	:	Probability that a calling CBO terminal goes from the talking state to the silent state.
p4	:	Probability that a calling CBO terminal goes from the silent state to the talking state.
$p_{arrival}$	:	DBO packet arrival rate at the system. This stream is split into inbound and outbound traffic.
p_{bl}	:	Allowable blocking probability.
p_d	:	Probability of retransmitting a backlogged DBO packet, in a free slot by a DBO terminal.
p_{d0}	:	Probability of arrival of a new DBO packet at a DBO terminal during one slot period.
p_{free}	:	Probability that a slot is free for DBO traffic.
p_g	:	Probability of retransmitting a backlogged DBO packet, in a free slot by the GBS.
p_{g0}	:	Probability of arrival of a new DBO packet at the GBS during one slot period.
Pr{ }	:	Probability.
PRMA	:	Packet Reservation Multiple Access.
prob(x)	:	Boolean function which returns "TRUE" with probability (x) and "FALSE" with probability (1-x).

$p_{succ\ DBO}$: Probability of a successful DBO packet transmission by a DBO terminal in a free slot.

$p_{succ\ GBS}$: Probability of a successful DBO packet transmission by the GBS in a free slot.

p_{talk} : Fraction of talkspurts in speech traffic.

$p_{thr\ DBO}$: Total throughput for all DBO terminals.

$p_{thr\ GBS}$: DBO throughput for GBS.

$p_{transmit\ GBS}$: Probability the GBS transmits a packet in a free slot.

$p_{transmit\ DBO}$: Probability a DBO terminal transmits a packet in a free slot.

rtr : DBO terminal(s) or GBS retransmit(s).

$\overline{rtr}$: DBO terminal(s) or GBS do(es) not retransmit.

slpfr : Number of slots in every frame.

st : State.

$syst_{thr}$: System throughput.

T_ack : Time necessary to generate and transmit an acknowledgement.

t_{back} : DBO terminal(s) in backlogged mode.

TDMA : Time Division Multiple Access.

t_{orig} : DBO terminal(s) in originating mode.

trm : DBO terminal(s) or GBS transmit(s).

$\overline{trm}$: DBO terminal(s) or GBS do(es) not transmit.

T_{slot} : Duration of one slot period.

t_{c_hld} : CBO call holding time [min].

$t_{del\ DBO}$: Average delay of a DBO packet in a DBO terminal in T_{slot} units.

$t_{del\ GBS}$: Average delay of a DBO packet in the GBS in T_{slot} units.

UHF : Ultra High Frequency.

$v_{steady\ state}$: Vector with steady state distribution of MARKOV model.

v_t : State probability vector of MARKOV model at time t.

X : Stochastic variable, which represents the number of slots between the current slot and the slot in which the next packet arrives at a DBO station.

λ_c : CBO call arrival intensity for every free CBO source [$hour^{-1}$].

Δnr_ncon : Variation of number of CBO users, which are in the state "NO CONNECTION", during a CBO traffic simulation run.

Δnr_slnt	:	Variation of number of CBO users, which are in the state "CONNECTION SILENT", during a CBO traffic simulation run.
Δnr_talk	:	Variation of number of CBO users, which are in the state "CONNECTION TALKING", during a CBO traffic simulation run.
μ_c	:	Call completion rate [min^{-1}].
τ_{sim}	:	Duration of CBO simulation interval.
τ_{slnt}	:	Average duration of silent period for a CBO speech terminal.
τ_{talk}	:	Average duration of talkspurt period for a CBO speech terminal.
$\wedge$	:	Logical AND operator.

CONTENTS.

1 INTRODUCTION.

Wireless Access and integration of services are expected to be two major items in the office of the future. Wireless access avoids the pulling of cables to every foreseeable location, and provides flexibility in the placement of terminals. Integration is required because together with the well known services like telephone and terminal communication, a lot of new ones, for example videophone and data inquiry, are likely to penetrate the office environment.

According to [1], electronic traffic can be separated in two categories. The first one has a constant bandwidth demand and is called the Continuous Bitstream Oriented (CBO) traffic. The second traffic type, called Discontinuous Bitstream Oriented (DBO), has a more bursty character and therefore has a variable bandwidth demand. In figure 1 some examples of both types are depicted.

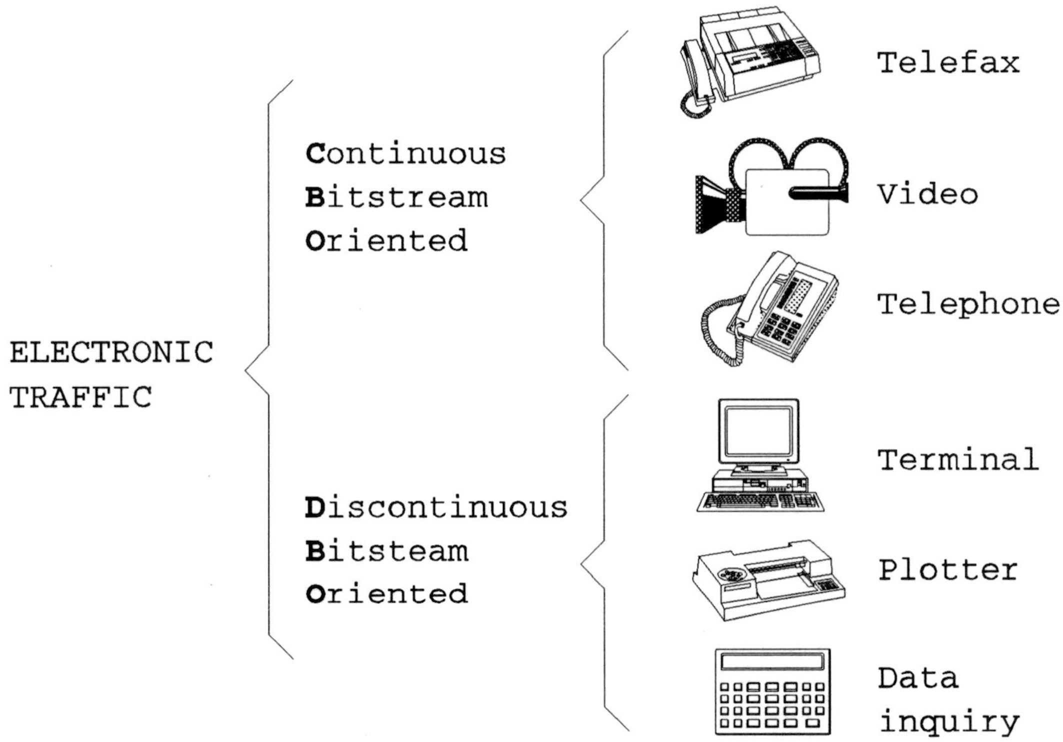

Figure 1: Continuous and Discontinuous Bitstream Oriented electronic traffic.

For CBO traffic the low delay requirements are the most important, and the error rate has a lower priority as compared to the DBO traffic. On the other hand for the DBO traffic very high demands are placed on data integrity, whereas some delay is acceptable.

To serve traffic types in both categories a detailed qualitative design of a wireless office communication system is given in [2]. As a result a cellular system is proposed in there. This system consists of several separate groups, one in each cell as shown in figure 2. Each group contains a mixture of CBO and DBO users, and a central Group Base Station (GBS). All GBSs are connected by a high speed backbone network.

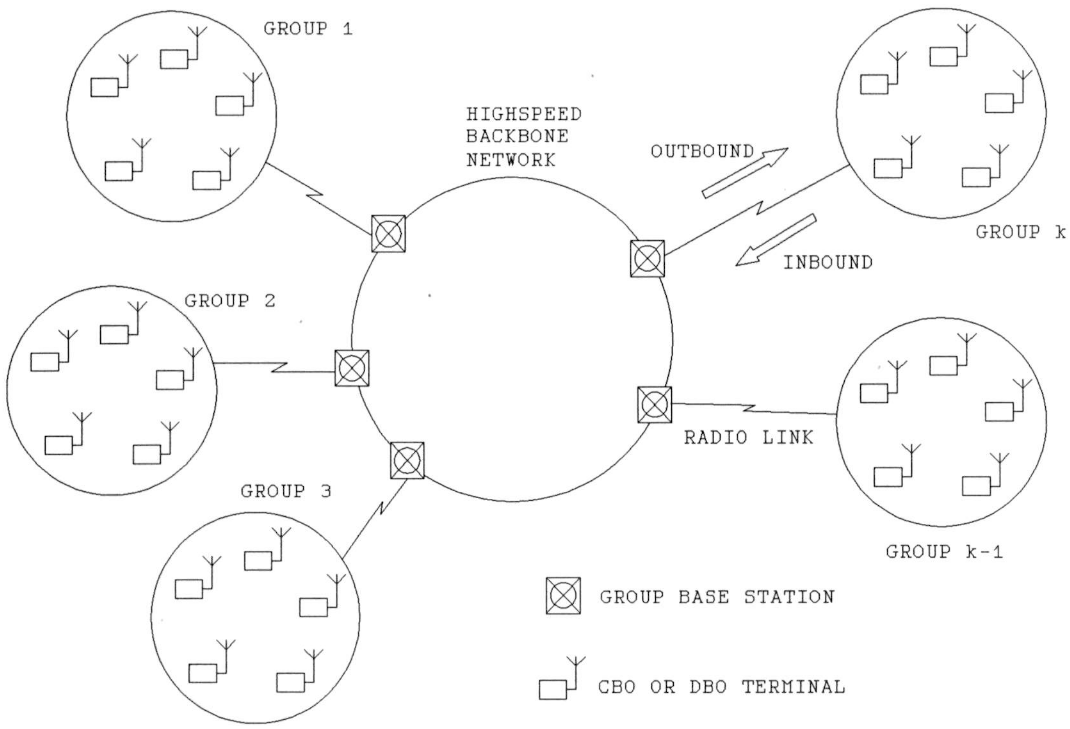

Figure 2 : Network structure for wireless office communications.

Each group has its own radio link in the UHF frequency region in the range from 1880-1900 Mhz, which is available for this application in Europe [3]. All DBO and CBO terminals and the GBS of one group have access to this radio link. Data from the GBS towards the group terminals is called outbound traffic and the opposite direction inbound traffic. In this report the protocol used on this radio link is investigated.

To achieve a high spectrum efficiency the cell sizes have to be as small as possible [4]. Because of this reason a system with small groups is considered. Each cell contains at maximum 20 DBO and 20 CBO users.

Speech is at the moment the most spread CBO traffic type, and will probably also demand a high portion of the systems capacity in the future. A speech source creates a pattern of talking periods (called talkspurts) and silent periods [5]. With a speech detector these two periods can be separated, so the bandwidth left unused in silent periods can be used by other sources.

Strictly considered, speech traffic does not produce a constant bit-stream, because of the on-off pattern. However during talkspurt periods a constant bitstream is generated, which has the above mentioned CBO requirements. This is why speech traffic in this report is considered as a CBO traffic type.

Several protocols have been published for the integration of speech and data traffic, and make use of the available bandwidth in the silent periods. One of them is the well known Packet Reservation Multiple Access (PRMA) protocol proposed in [6]. This protocol does multiplexing on a talkspurt level, i.e. a speech source has to reserve the necessary bandwidth at the beginning of every talkspurt. When such a reservation takes too much time, speech data is discarded, to avoid unacceptable delays. This causes front end clipping at the beginning of talkspurts.

To avoid discarding of CBO data, whenever the necessary bandwidth has to be reserved, a new Circuit Reservation Multiple Access (CRMA) protocol is presented and investigated in this report. CRMA guarantees the required bandwidth for the CBO users whenever a connection is allocated. The remaining link capacity is left for contention for the transportation of data by the DBO users.

For the performance analysis presented the chapters 3-5, only two types of traffic are considered. Speech as representative of the CBO traffic, and data packets with a geometrically distributed inter arrival time, generated by the DBO users.

In chapter 2 a description of the CRMA protocol is given.
The analytical models of both the CBO and the DBO traffic are presented in chapter 3. Chapter 4 describes the simulation models of both types. The results of both the analytical and the simulation models are depicted and compared in chapter 5.
Chapter 6 contains an evaluation of the CRMA protocol. Besides this, several other protocols for mixed speech/data traffic are described in that chapter and compared with CRMA.
In chapter 7 the conclusions and recommendations are given.

2 DESCRIPTION OF THE CRMA PROTOCOL.

2.1 Introduction to the CRMA protocol.

Most existing protocols for mixed traffic give a sufficient performance for speech traffic which can suffer a loss probability of 1% with negligible decrease in perceptual quality. [7] For CBO data which are not allowed to have that much data loss, another protocol, which is called the Circuit Reservation Multiple Access (CRMA) protocol, is proposed. CRMA controls the data transport over a half duplex radio link. Terminals with divergent service requirements and a group base station (GBS), all located in a small geographical area, transport their data over a common radio channel. Time division multiplexing is used on this channel, to share the total link capacity between all CBO and DBO users in the group and the GBS.

The CRMA protocol is organised around time frames with duration matched to the periodic rate of the slowest CBO source. Each frame is split into a fixed number of equal time slots, in which data can be transmitted.

The CRMA protocol can be described as follows :

- The protocol uses a "half duplex" or "two way alternate" radio link. So all CBO and DBO sources and the GBS belonging to one group share a common channel.
- A CBO source first has to contend for a connection. When it is assigned a connection by the GBS, one or more time slots in the frame are reserved for this source. For speech traffic for example, one slot is reserved for the inbound, and one for the outbound packets of the duplex connection between source and destination.
- When the connection period is finished, this is signalled to the GBS, by the CBO source, and the slot(s) is (are) available for contention for other traffic.
- When a slot does not contain any CBO packet it may be used for DBO packets. This happens in periods of silence between the talkspurts, or when a channel is not reserved for a connection by a CBO source.

- When a DBO source wants to transmit a packet in a specific slot, it listens to the channel for a short period at the beginning of that slot. This period is long enough to assure that no CBO packet is transmitted by one of the group terminals or the GBS. When the DBO terminal does not sense a carrier of a CBO source, the slot is accessed with a fixed probability.
- When a DBO packet is successfully transmitted, an acknowledgement is given by the receiving station.
- The contention for a connection by a CBO source is handled just like a DBO source. When a "request connection signal" successfully reaches the GBS, this station signals the CBO source, which slot(s) may be used.
- The CBO packet is transmitted from the beginning of the slot to the end of the slot. For voice traffic no acknowledgment is given by the receiving station and the packets are not buffered in the transmitting station.
- For CBO traffic which requires a very low data loss probability there are two possibilities. The first one is to apply an error correcting code. The second is to add an acknowledgement, but then the low delay requirements may be violated. In latter case also a buffer in the transmitting station must be added to make retransmissions possible.
- The frame length has to be derived from the slowest CBO traffic type. This type is assigned one slot in every frame, or two in case of a duplex end to end connection. Faster CBO traffic sources can be assigned multiple slots in every frame, to make a higher bitrate possible.

2.2 Accessing the radio link with CRMA.

Following figure 3 a description of the access mechanism of the CRMA protocol will be given. In the next sections the timing of the transmission is worked out.

A slot can contain three types of data packets.

i) CONTROL data packets

   This type of packet is generated in the GBS, and is transmitted in a fixed timeslot. All DBO and CBO terminals receive this CONTROL data.

ii) CBO data packets

When a connection is built up by a CBO source a timeslot is reserved for this source. This source may be one of the group CBO terminals or the GBS, and transmit a CBO data packet during this reserved timeslot. In case of a duplex connection, for example a telephone call, two timeslots are reserved, one for the inbound and one for the outbound data packets.

iii) DBO data packets

When a slot is not assigned for CONTROL data and not reserved or not used (for example in silent periods between talkspurts) for a CBO data packet, it is free for contention for DBO data sources. These sources may be one of the group DBO terminals or the GBS. If a slot is free and a DBO terminal has a packet for transmission, the packet is placed in the free slot with a fixed probability. If more than one DBO terminal transmits at the same time a collision will occur. No capture is assumed. So when two packets collide none of them is successfully received.

Inbound data packets are placed on the radio link by the DBO terminals and picked from this link by the GBS. The GBS will send these data packets over the backbone network to the GBS of the destination group.

Outbound data packets are first picked from the backbone network by the GBS and then placed in one of the link timeslots. The destination terminal will pick the packet from the link.

Control packets are placed on the radio link by the GBS and picked from the link by all CBO as well as DBO terminals.

In figure 3 there are 9 numbered timeslots. For each of them a short description will be given.

Timeslot 1: The GBS sends a control packet. All CBO and DBO terminals pick this packet from the radio link.

Timeslot 2: CBO 1 sends a packet. The GBS receives it and places it on the backbone network. If the destination is one of the terminals of its own group, the GBS places the packet back on the radio link.

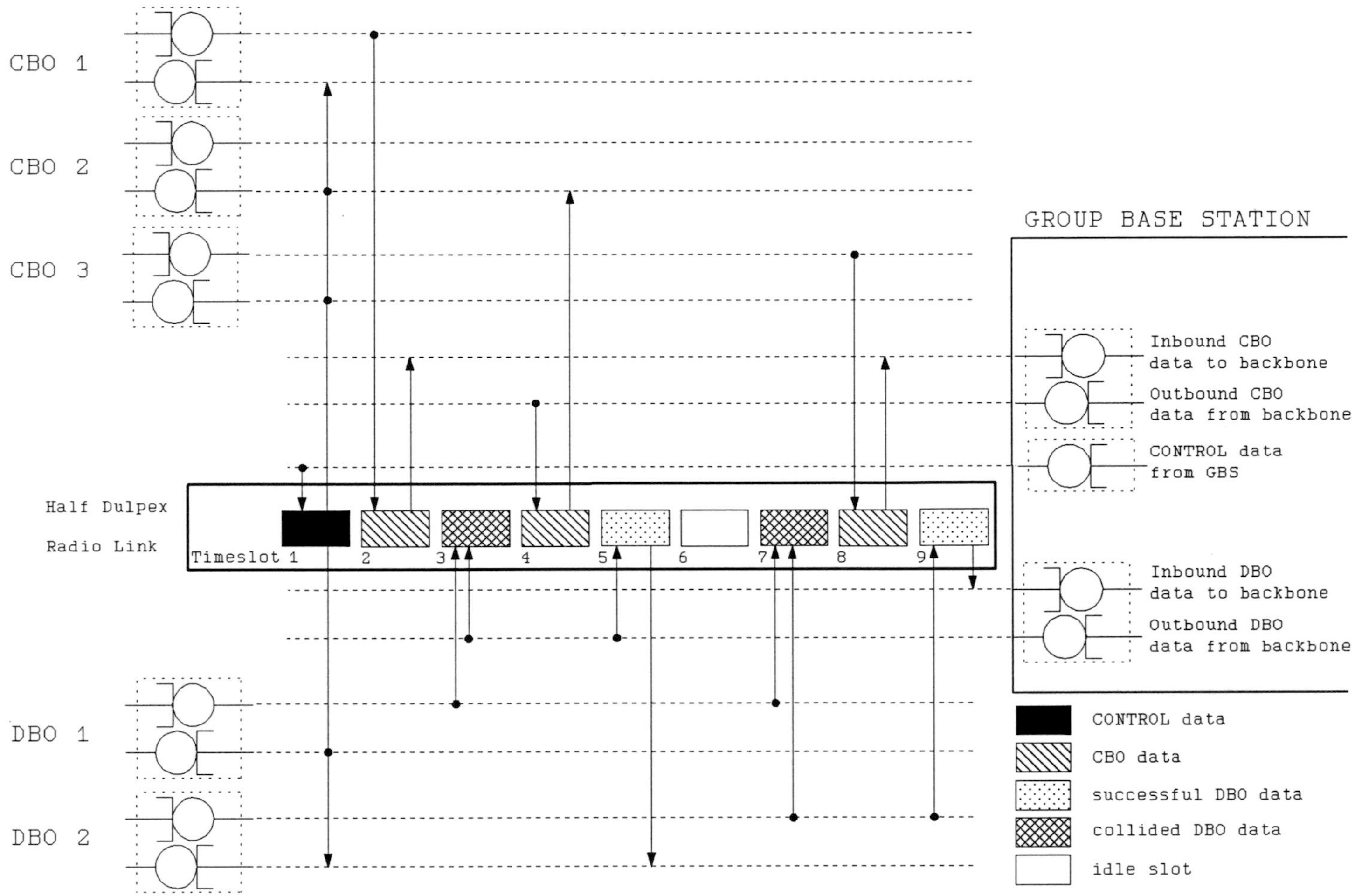

Figure 3 : Accessing the half duplex radio link with the CRMA protocol.

Timeslot 3: DBO 1 and the GBS have seen a free timeslot and both transmit a DBO packet. A collision occurs and both packets get lost.

Timeslot 4: The GBS sends a CBO packet to the CBO 2 terminal.

Timeslot 5: The GBS sends a DBO packet to DBO 2. No other terminals have sent a packet so the transmission is successful.

Timeslot 6: No station has transmitted data in this timeslot. Therefore the channel is idle during this slot period.

Timeslot 7: See timeslot 3. Only in this case DBO 1 and DBO 2 try to access the free timeslot.

Timeslot 8: CBO 3 sends a packet to the GBS, which transmits it over the backbone network to the destination.

Timeslot 9: DBO 2 successfully transmits a packet to the GBS.

2.3 Timing of the transmission of a CBO packet.

In figure 4 the timing diagram of a CBO packet transmission is given. This transmission may be done by one of the CBO terminals or the GBS.

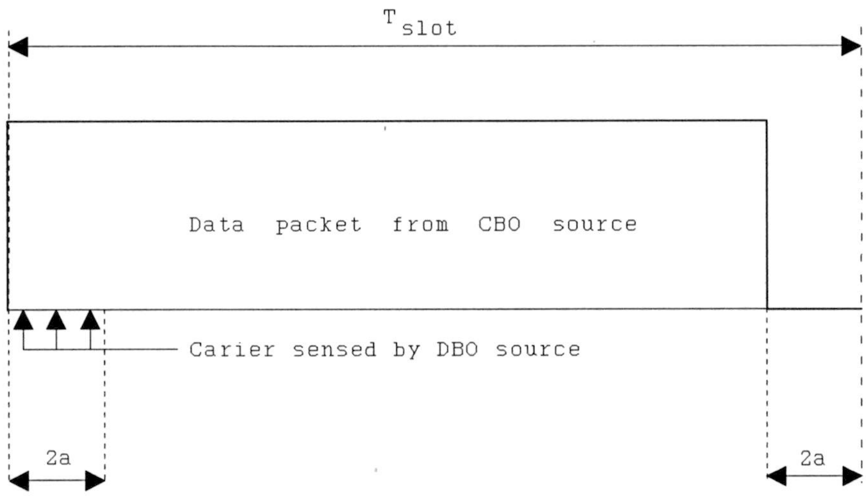

Figure 4 : Timing of a CBO packet transmission.

Directly at the beginning of the timeslot the CBO source starts the transmission. It continues the transmission almost until the end of the timeslot. Only at the end a short time, which lasts "2a" no transmission is done, with "a" the worst case propagation delay.

A lot of measurements to indoor propagation characteristics have been done. From [8] and [9] it can be concluded that the worst case propagation delay in an indoor environment does not exceed 1 μsec. This includes a multipath time delay spread of about 400 nsec. It can easily be calculated that with this propagation delay, the maximum cell diameter equals 300 m.

For CBO packets no acknowledgement is given. This is why some packets may be lost because of noise.

At the beginning the channel is sensed by a DBO terminal, which wants to transmit. Because it sees a carrier it does not try to access the channel in this timeslot.

Because a slotted protocol is used, the internal clocks of all terminals must be synchronised. The GBS has the masterclock and sends at the beginning of every CONTROL packet a synchronization signal for adjusting the internal clocks of all terminals. Due to the propagation delay the clocks of the terminals will lag with the masterclock. The furthest terminal will experience the worst case propagation delay "a". To avoid collision of bits from packets in adjacent slots, we must keep account with this synchronisation time, and introduce a silent gap equal to "a" at the end of each slot.

The propagation delay is, next to this synchronisation aspect, also responsible for some time delay between the transmission and the receiving of a packet. Before starting the transmission of the first bits in a new slot, it must be certain that the last bits in the former slot have been received. This is why an extra silent gap, with the duration of "a" must be added at the end of each slot.

Both above mentioned aspects result in a necessary gap of "2a" at the end of each slot. This is why a CBO source cannot transmit during the complete slot time.

The timing of a CONTROL packet is just like that of a CBO packet.

2.4 Timing of the transmission of a DBO packet.

In figure 5 the timing diagram for transmitting a DBO packet is shown. A terminal or the GBS, which wants to transmit a DBO packet first has to wait a short time to start transmission.

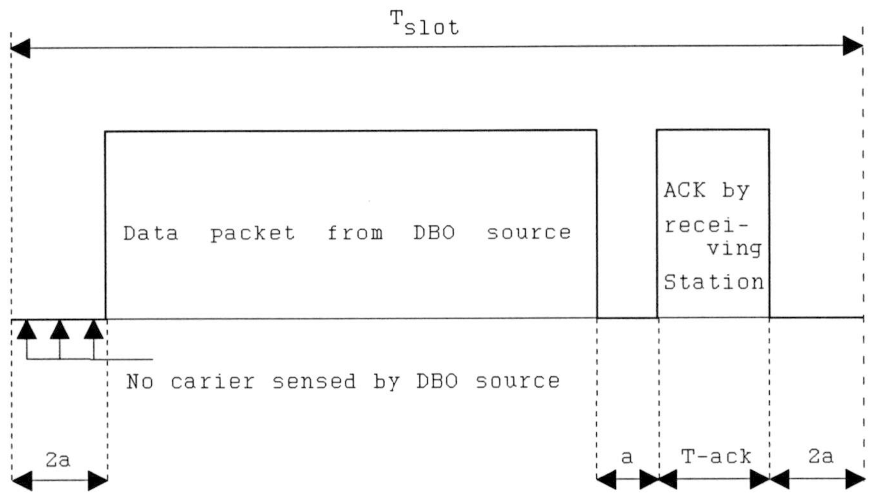

Figure 5 : Timing of a DBO packet transmission.

Due to the synchronisation lag, a DBO terminal first has to wait a time "a" to be sure that a CBO terminal may have started transmission.
On top of this it also has to wait a period "a" to be certain, that a signal from the furthest station is received. This is because of the propagation delay.

This is why a DBO terminal senses the channel for a period of "2a" before transmitting, to find out if a carrier is transmitted by one of the CBO sources. If no carrier is sensed the channel is free for contention by one of the DBO sources, and the DBO terminal sends its packet.
If no other DBO source has transmitted a data packet in the same slot and the noise level is not too high, the packet will be received successfully.
The transmission has to be short enough, to make an acknowledgement in the same timeslot by the receiving station possible. Therefore it takes the propagation time "a" for the last bits of the DBO packet to reach the

receiving station. In this case the synchronisation lag has no influence, because the receiving station, exactly knows when the last bits of the packet are received.
After receiving the last bits, the destination station has to check the incoming packet, and sends an acknowledgement if the transmission has been successful. The time "T_ack" includes the processing time and the time to transmit the acknowledgement packet.

Because of the reasons mentioned in the former subsection, it is necessary to introduce a silent period with a duration of "2a" at the end of each slot period.

3 THE ANALYTICAL MODEL.

In this chapter the analytical model is described, which calculates the throughput of the CBO traffic and the throughput and the delay of the DBO traffic produced by the group DBO terminals and the GBS.

For both the analytical model and the simulation model, which is discussed in the next chapter, only two traffic types are taken into account for simplicity. Speech traffic is taken as the representative of the CBO type. For the DBO stations, only packet arrivals are considered with a geometrically distributed inter arrival time.
The transportation of the CBO data is independent of that of DBO data. Therefore first a model for the speech traffic will be discussed hereafter, followed by a model for the DBO data.

3.1 The analytical model for the CBO traffic.

For the CBO traffic it is assumed that the group CBO terminals only produce calls and never receive a call. Besides this, the destination terminals are assumed to belong to an infinite population. The probability of blocking, because of a busy destination is neglected.
For every CBO circuit 2 slots are assigned, one for the inbound and one for the outbound data packets of the full duplex end to end connection. So first the number of active circuits has to be determined.

Because small cell sizes are assumed, with a limited number of CBO users, we cannot use the ERLANG loss model, which is only valid for a large number of users. For that reason the ENGSET model is used, which takes into account a calling customer cannot produce a new call while it is already calling.
A detailed description of the ENGSET loss model can be found in [10] and [11]. In figure 6 the state transition diagram of this ENGSET model is shown, indicating the number of calls in progress in the group. This model is valid only, if inter arrival and holding times are exponentially exponentially distributed, which will be considered in this study. Formula 1 however, which gives the calculation of the state probabili-

ties, is also valid for any distribution of inter arrival and holding time with means $1/\lambda_c$ and $1/\mu_c$ respectively.

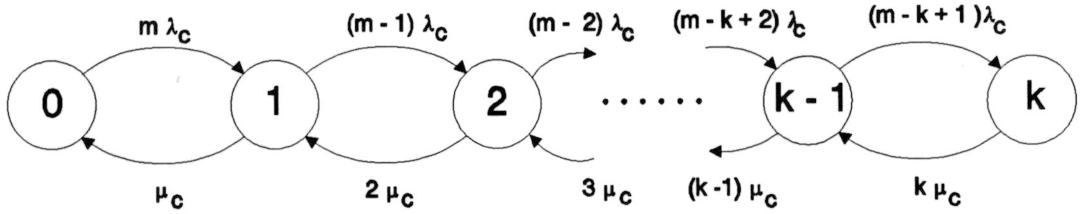

Figure 6 : State diagram of the Engset model

With,

k : Maximum allowed number of CBO circuits per link.

m : Number of CBO users in the group.

λ_c : CBO call arrival rate for every free CBO source [hour $^{-1}$].

μ_c : Call completion rate [min $^{-1}$].

The probability of state j can be calculated with :

$$p_j = \frac{\binom{m}{j} \left(\frac{\lambda_c}{60 \times \mu_c}\right)^j}{\sum_{i=0}^{k} \binom{m}{i} \left(\frac{\lambda_c}{60 \times \mu_c}\right)^i} . \qquad 0 \le j \le k \qquad \textbf{(1)}$$

The average number of CBO circuits equals :

$$CBO_{cirq} = \sum_{j=0}^{k} j \times p_j . \qquad \textbf{(2)}$$

According to [12] the average duration of the talkspurts and silent periods in speech are respectively:

τ_{talk} = 1 sec,

τ_{slnt} = 1,35 sec.

This yields an average talkspurt fraction of: "p_{talk} = 0,426".

Taken into account that every circuit requires two slots, and only during talkspurt periods CBO data is transported, the average number of slots assigned to CBO traffic in every frame can be calculated with:

$$CBO_{sl} = 2 \times CBO_{circ} \times p_{talk} \; . \qquad \textbf{(3)}$$

There are two restriction, which limit the number of active CBO calls.

i) The first restriction is the number of slots in the frame. If two slots are assigned for every connection the maximum number of simultaneous connections equals half the number of slots in the frame. CRMA is intended to be used in a cellular structure with a limited number of users. Because of this reason this restriction is considered to give no constraint on the system performance and therefore neglected in this study.

ii) The second restriction is caused by the call blocking probability. This is introduced to achieve a minimum level of the link capacity for the DBO traffic. If a fixed minimum is chosen for this DBO capacity, the quality of service for the CBO traffic could be too low because of a high blocking rate. For this reason a compromise is made between the minimum DBO capacity and the allowed blocking probability for CBO traffic.
For the CRMA system, the maximum number of circuits for speech traffic "k" is determined by the maximum allowed blocking probability; "p_{bl}".

Given the maximum allowable blocking probability the number of circuits "k" required, can be calculated with the recursive procedure for the ENGSET distribution, which is described in [10]

For this the reciprocal value of the blocking probability for m sources, with a call arrival intensity per free source λ_c, is defined as :

$$J_i\ (\ m, \lambda_c\ )\ \triangleq\ \frac{1}{p_{bl}}\ . \tag{4}$$

The recursive procedure is now as follows:

Start with:

$$J_0(\ m, \lambda_c\ )\ =\ 1\ . \tag{5}$$

The recursion for $J_i(m,\lambda_c)$ equals :

$$J_i(\ m, \lambda_c\ )\ =\ J_{i-1}(\ m, \lambda_c\ )\,\frac{i \times 60 \times \mu_c}{(m\ -\ i)\,\lambda_c}\ +\ 1\ .\qquad i\ =\ 1,2,..,k \tag{6}$$

Increase the number of CBO circuits "k" as long as :

$$\frac{1}{J_k\ (\ m, \lambda_c\ )}\ >\ p_{bl}\ . \tag{7}$$

3.2 The analytical model for the DBO traffic.

In this section several items are discussed. First the packet arrival model and the state transition model for a DBO terminal and the GBS are discussed. Thereafter the access mechanism of the CRMA protocol for a station which wants to transmit a DBO packet is given. In the following section a MARKOV model is described, which gives the number of backlogged terminals and whether or not the GBS is backlogged. Thereafter the steady state distribution of this MARKOV model is calculated. The last two subsections contain the calculation of the throughputs and the packet delays respectively.

3.2.1 The DBO station states.

A DBO station can be one of the DBO terminals or the GBS. The probability of arrival of a packet at such a DBO station in a slot period, is assumed constant and independent of previous arrival events.
Consider a stochastic variable X, which is defined by the number of slots between the current slot and the slot in which the next packet arrives. If p is the probability of a packet arrival in one slot period, then the probability that the first packet arrives in the i^{th} time slot from the current time slot can then be calculated with:

$$Pr\{ X = i \} = (1 - p)^{i-1} \times p . \qquad i = 1,2,... \qquad \textbf{(8)}$$

This results in a geometrically distributed time between two data deliveries. This inter arrival time has an average value of "1/p" slot periods [10]. For any of the DBO terminals, new packets arrive in a time slot with probability p_{d0}. This arrival probability is p_{g0} for the GBS.

When a DBO packet is lost, for instance by collision with another data packet, it has to be retransmitted because this kind of traffic type is not allowed to have any data loss. This is why data packets from DBO sources are buffered, to make a retransmission possible. To restrict the size of the model and the amount of calculations, the DBO terminals and the GBS are modelled with buffer space for only one DBO data packet.

Three possible modes are described for this type of data terminals. See figure 7. The originating mode (ORIG), the transmission mode (TRANSMIT), and the backlog mode (BACK). At the beginning of a slot period a station can only be in the originating mode or the backlogged mode. If a station transmits (trm) or retransmits (rtr), it will only enter the transmission mode until the end of the current slot period. At the end of this slot period the station will enter the originating mode if the transmission has been successful or to the backlogged mode in case of a collision.

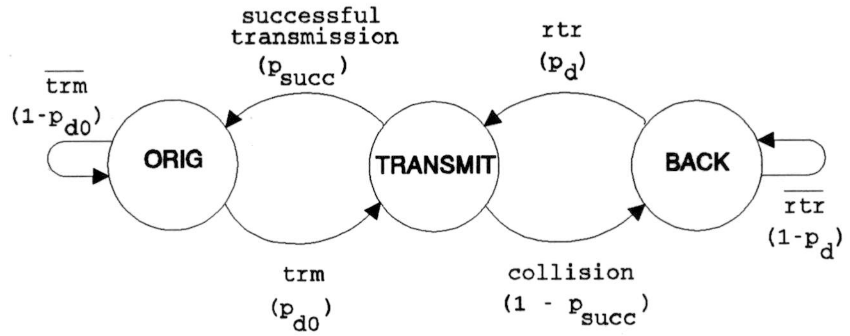

Figure 7 : DBO station states and transitions. (p_{d0} and p_d for DBO terminals, replaced by p_{g0} and p_g for GBS).

If the station is in originating mode and a packet has arrived in the last slot period, this packet is transmitted in the next available slot with probability 1. If the station was in backlogged mode new packets are discarded.

When a terminal is backlogged the collided packet is retransmitted in the first free slot with probability p_d for a DBO terminal, and with probability p_g for the GBS.

The probability that a packet is successfully transmitted (p_{succ}) or not ($1-p_{succ}$), is dependent on the state of the MARKOV model, which will be described in the next subsections.

It can be concluded, that if a DBO terminal is in the originating mode it transmits in a free slot with probability :

$$Pr\{ \, trm_{DBO} \, \} \; = \; p_{d0} \; . \tag{9}$$

With p_{d0} the probability of a new packet arrival during one slot period at a DBO terminal, which can be calculated with:

$$p_{d0} = \frac{\text{inb\_outb} \times p_{arrival}}{nr_{DBO} \times \{ 1 + \text{inb\_outb}\}} \quad . \tag{10}$$

with:

$p_{arrival}$: Packet arrival rate at the system. This rate is split into inbound and outbound traffic.

nr_{DBO} : Number of DBO users.

inb_outb : Ratio between inbound and outbound packet arrival rates.

If the DBO terminal is backlogged it retransmits with probability:

$$\Pr\{rtr_{DBO}\} = p_d \quad . \tag{11}$$

If the GBS is in the originating mode it transmits a DBO packet in a free slot with probability :

$$\Pr\{trm_{GBS}\} = p_{g0} \quad . \tag{12}$$

With p_{g0} the probability of a new packet arrival during one slot period at the GBS, which can be calculated with:

$$p_{g0} = \frac{p_{arrival}}{1 + \text{inb\_outb}} \quad . \tag{13}$$

If the GBS is backlogged it retransmits with probability:

$$\Pr\{rtr_{GBS}\} = p_g \quad . \tag{14}$$

3.2.2 The DBO station access mechanism.

The descriptions of the CRMA protocol given in chapter 2 and the DBO station states in the former subsection, lead to the following access mechanism for a station (a DBO terminal or the GBS), which wants to transmit DBO data:

i) The station senses the channel for a CBO carrier during a period "2a" at the beginning of the slot.

ii) If the channel is sensed busy, the station waits until the beginning of the next slot and starts again.

iii) If the channel is sensed idle there are three possibilities:

a) The station was in originating mode AND a new packet has arrived in the last slot period.
The newly arrived packet is transmitted.

b) The station was in originating mode AND a no new packet has arrived in the last slot period.
No transmission is done.

c) The station was backlogged
The backlogged packet is transmitted with probability "p_d" for a DBO terminal and with probability "p_g" for the GBS.

3.2.3 The MARKOV model.

The state of the CRMA system that consists of "n" DBO users and the GBS can be described at the beginning of every slot period, by the number of backlogged terminals and whether or not the GBS is backlogged. With a discrete time MARKOV chain, as described in [13], this state can be characterised, and the necessary information for the analysis can be derived.
To limit the size of the model arrivals during CONTROL and CBO slots are neglected. Therefore for the MARKOV model only the free slots are relevant. If a slot is not free the state of the MARKOV model does not change. The only thing that does change during CONTROL or CBO slots is the age of the backlogged packets. This is taken into account with the formulas (38) and (39). Therefore for the calculation of the MARKOV model only free slots are considered.

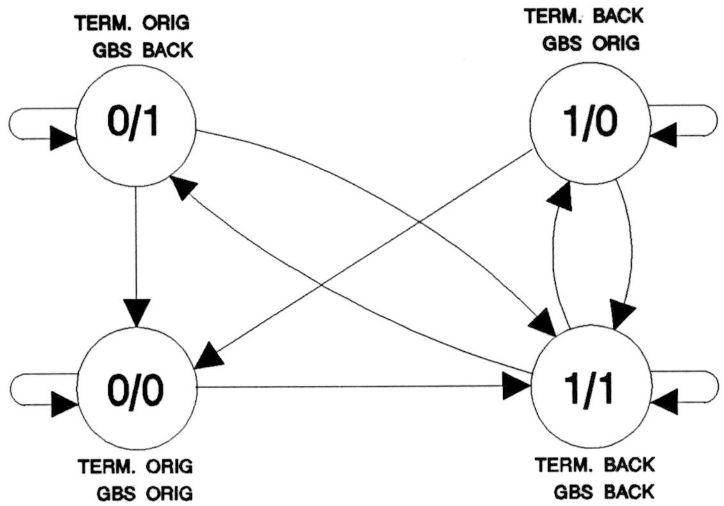

Fig. 8: State transition diagram with only one DBO terminal (TERM.)and the GBS.

In figure 8 the MARKOV model of a system with only one DBO terminal and the GBS is depicted.
The system is in state "0/0" if both the terminal and the GBS are in originating mode. State "1/1" is entered if the terminal and the GBS transmit in the same timeslot. If in state "1/1" the terminal does retransmit and the GBS does not, the system will enter state "0/1", which indicates that only the GBS is backlogged. If on the other hand in state "1/1" the GBS retransmit and the terminal is quiet, the system will go to state "1/0", indicating the terminal is backlogged. Other transitions are also possible as indicated in figure 8.

In figure 9 the general model is given for any number "n" of DBO terminals. Every state in this figure is characterised by the number of backlogged DBO terminals and whether or not the GBS is backlogged.
For example state "3/0" indicates that 3 terminals are backlogged and the GBS is in the originating mode. In state "3/1" there are also three backlogged terminals but the GBS is backlogged as well.

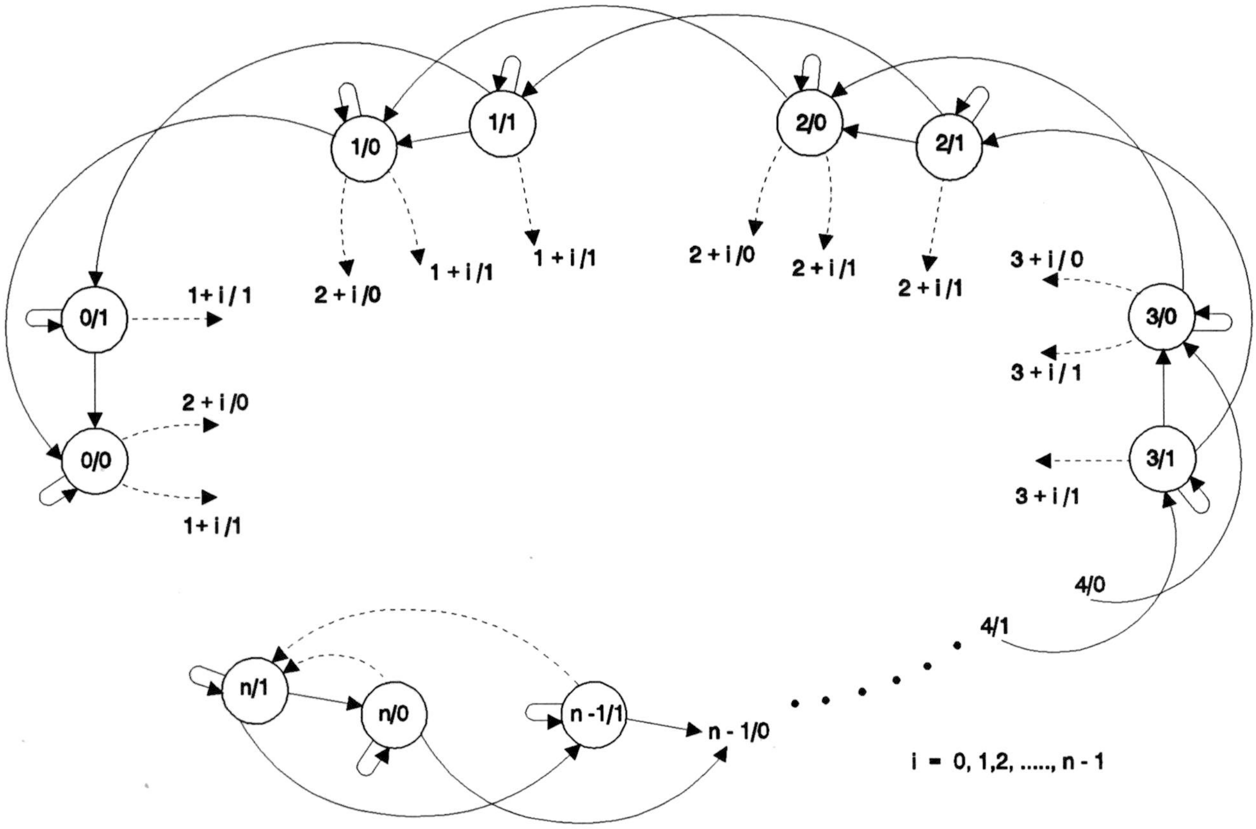

Figure 9 : State transition diagram of backlogged DBO terminals.

A dashed transition line in figure 9 indicates that a collision has occurred. A solid transition line to another state indicates a successful transmission.
If the transition is to the same state, there could have been a successful transmission, no transmission at all, or a collision of backlogged packets may have occurred.

Transitions not given in this figure, do by definition not take place. For every transition first the state transition will be given hereafter. Following on this the probability is presented in "words".

Here,

t_{orig}	means	: DBO terminal(s) in originating mode
t_{back}	means	: DBO terminal(s) in backlogged mode.
$_{trm}$	means	: transmit(s)
$_{rtr}$	means	: retransmit(s)
$\overline{_{trm}}$	means	: do(es) not transmit
$\overline{_{rtr}}$	means	: do(es) not retransmit
$\wedge$	means	: logical AND

For every transition a formula is given, with which the probability can be calculated. Besides each formula the range of the variables are given. On this point is noticed that always counts "$0 \leq j \leq n$".

Every state transition, which is not covered by one of the formulas 16 – 26, has a transition probability zero.

In this report the binomial probability function will be denoted as:

$$\text{bin}\ (a,b,p)\ \triangleq \binom{b}{a} p^{a}\ (1-p)^{b-a}\ . \qquad \textbf{(15)}$$

Notice that an originating DBO terminal transmit with probability "p_{do}", and a backlogged terminal retransmits with probability "p_d".
If the GBS is in originating mode it transmits with probability "p_{g0}", and retransmits with "p_g" in the backlogged mode.

j/0 → j/0

Pr { all $t_{orig}\ \overline{_{trm}}$ $\wedge$ all $t_{back}\ \overline{_{rtr}}$ } +
Pr { GBS $\overline{_{trm}}$ $\wedge$ 1 $t_{orig\ trm}$ $\wedge$ all $t_{back}\ \overline{_{rtr}}$ } +
Pr { GBS $\overline{_{trm}}$ $\wedge$ all $t_{orig}\ \overline{_{trm}}$ $\wedge$ 2 or more $t_{back\ rtr}$ }

$$j/0 \rightarrow j/0 : \begin{cases} (1-p_{d0})^{n-j} \times (1-p_d)^{j} + \\ (1-p_{g0}) \times \text{bin}(1,n-j,p_{d0}) \times (1-p_d)^{j} + \\ (1-p_{g0}) \times (1-p_{d0})^{n-j} \times \{1-(1-p_d)^{j} - \text{bin}(1,j,p_d)\}\ . \end{cases} \qquad \textbf{(16)}$$

$j/0 \rightarrow j/1$

$\Pr\{\ GBS_{\ trm} \wedge \text{all } t_{orig\ \overline{trm}} \wedge 1 \text{ or more } t_{back\ rtr}\ \}$

$$j/0 \rightarrow j/1:\ (p_{g0}) \times (1-p_{d0})^{n-j} \times \{1-(1-p_d)^j\}. \tag{17}$$

$j/0 \rightarrow j\text{-}1/0$

$\Pr\{\ GBS_{\ \overline{trm}} \wedge \text{all } t_{orig\ \overline{trm}} \wedge 1\ t_{back\ rtr}\ \}$

$$j/0 \rightarrow j-1/0:\ (1-p_{g0}) \times (1-p_{d0})^{n-j} \times \mathrm{bin}(1,j,p_d). \tag{18}$$

$j/0 \rightarrow j+1/0$

$\Pr\{\ GBS_{\ \overline{trm}} \wedge 1\ t_{orig\ trm} \wedge 1 \text{ or more } t_{back\ rtr}\ \}$

$$j/0 \rightarrow j+1/0:\ (1-p_{g0}) \times \mathrm{bin}(1,n-j,p_{d0}) \times (1-(1-p_d)^j). \tag{19}$$

$j/0 \rightarrow j+i/0$

$\Pr\{\ GBS_{\ \overline{trm}} \wedge i\ t_{orig\ trm}\ \}$

$$j/0 \rightarrow j+i/0:\ (1-p_{g0}) \times \mathrm{bin}(i,n-j,p_{d0}). \qquad 2 \le i \le j \tag{20}$$

$j/0 \rightarrow j+i/1$

$\Pr\{\ GBS_{\ trm} \wedge i\ t_{orig\ trm}\ \}$

$$j/0 \rightarrow j+i/1:\ p_{g0} \times \mathrm{bin}(i,n-j,p_{d0}). \qquad 1 \le i \le j \tag{21}$$

$j/1 \rightarrow j/1$

$\Pr\{\ GBS_{\ \overline{rtr}} \wedge \text{all } t_{orig\ \overline{trm}} \wedge \text{all } t_{back\ \overline{rtr}}\ \} +$

$\Pr\{\ GBS_{\ \overline{rtr}} \wedge 1\ t_{orig\ trm} \wedge \text{all } t_{back\ \overline{rtr}}\ \} +$

$\Pr\{\ GBS_{\ rtr} \wedge \text{all } t_{orig\ \overline{trm}} \wedge 1 \text{ or more } t_{back\ rtr}\ \} +$

$\Pr\{\ GBS_{\ \overline{rtr}} \wedge \text{all } t_{orig\ \overline{trm}} \wedge 2 \text{ or more } t_{back\ rtr}\ \}$

$$j/1 \rightarrow j/1: \begin{cases} (1-p_g) \times (1-p_{d0})^{n-j} \times (1-p_d)^j + \\ (1-p_g) \times \mathrm{bin}(1,n-j,p_{d0}) \times (1-p_d)^j + \\ p_g \times (1-p_{d0})^{n-j} \times \{1-(1-p_d)^j\} + \\ (1-p_g) \times (1-p_{d0})^{n-j} \times \{1-(1-p_d)^j - \mathrm{bin}(1,j,p_d)\}. \end{cases} \tag{22}$$

j/1 → j/0

Pr { GBS $_{rtr}$ ∧ all $t_{orig\ \overline{trm}}$ ∧ all $t_{back\ \overline{rtr}}$ }

$$j/1 \rightarrow j/0 : p_g \times (1-p_{d0})^{n-j} \times (1-p_d)^j . \qquad (23)$$

j/1 → j-1/1

Pr { GBS $_{\overline{rtr}}$ ∧ all $t_{orig\ \overline{trm}}$ ∧ 1 $t_{back\ rtr}$ }

$$j/1 \rightarrow j-1/1 : (1-p_g) \times (1-p_{d0})^{n-j} \times \mathrm{bin}(1,j,p_d) . \qquad (24)$$

j/1 → j+1/1

Pr { 1 $t_{orig\ trm}$ } −

Pr { GBS $_{\overline{rtr}}$ ∧ 1 $t_{orig\ trm}$ ∧ all $t_{back\ \overline{rtr}}$ }

$$j/1 \rightarrow j+1/1 : \mathrm{bin}(1,n-j,p_{d0}) \times \{ 1 - [(1-p_g) \times (1-p_d)^j] \} . \qquad (25)$$

j/1 → j+i/1

Pr { i $t_{orig\ trm}$ }

$$j/1 \rightarrow j+i/1 : \mathrm{bin}(i,n-j,p_{d0}) . \qquad 2 \le i \le n-j \qquad (26)$$

3.2.4 The steady state probabilities.

All transition probabilities, calculated with the formulas 16–26, are grouped together in a matrix **P**. In this matrix the element in row x and column y denotes the transition probability from state x to state y. Where (x div 2) respectively (y div 2) gives the number of backlogged DBO terminals. If (x mod 2) respectively (y mod 2) equals zero the GBS is in the originating mode. Otherwise if (x mod 2) respectively (y mod 2) equals one, the GBS is backlogged. The elements of each row must add up to 1.

If the current state probability distribution at time t is the row vector $\mathbf{v}_t$, then it can be found by multiplying the previous state probability vector at time t−1 ($\mathbf{v}_{t-1}$), with the transition matrix **P**.

So:

$$\mathbf{v}_t = \mathbf{v}_{t-1} \times \mathbf{P} \; . \tag{27}$$

On the condition that the model is ergodic [13], the MARKOV model will end up in a steady state after an infinite number of steps. For ergodicity two conditions have to be met. The first one is that the MARKOV chain is positive recurrent. This means that with positive probability, the chain, from any arbitrary state, returns in this same state, after a finite number of steps. The second condition is aperiodicity, which means that in the number of transitions between two specific states, no periodicity occurs.
For this study we are only interested in the steady state behaviour of the system. This means that the state probability vector does not change any more, after multiplying with the matrix **P**, and can therefore be defined by:

$$\mathbf{v}_{\text{steady state}} \triangleq \lim_{t \to \infty} \mathbf{v}_t \; . \tag{28}$$

This yields the following formula:

$$\mathbf{v}_{\text{steady state}} \times (\mathbf{P} - \mathbf{I}) = \mathbf{0} \; . \tag{29}$$

This describes a set of (2.n + 2) equations, which are not independent. To find the steady state vector we will have to make use of the fact that:

$$\sum_{st\,=\,0/0}^{n/1} \mathbf{v}_{\text{steady state}}(st) = 1 \; . \tag{30}$$

By exchanging one of the equations given by formula 29, with the one from formula 30, we get (2.n + 2) independent equations, which can be solved numerically. If the equation of formula 30 replaces the last one of formula 29 the steady state probability can be calculated with the following procedure also given in [10]:

i) Construct the matrix: $\mathbf{M} = \mathbf{P} - \mathbf{I}$.

ii) Replace the last column of $\mathbf{M}$ by ones.

iii) Construct a new vector $\mathbf{E} = [0,0, \ldots\ldots ,0,1]$.

iv) The steady state vector can be found from :

$$\mathbf{V}_{\text{steady state}} = \mathbf{E} \times \mathbf{M}^{-1} . \tag{31}$$

3.2.5 The system throughput.

The throughput is defined as the number of successful transmitted packets per slot.

The system throughput is built up by that for the CBO traffic, the total data transport by all DBO terminals (DBO) and the data transport by the GBS (GBS). To calculate the throughput for the DBO and GBS first the probability of a successful packet transmission in a free slot has to be calculated.

The probability of a successful packet transmission by a DBO terminal in a free slot shown in figure 7 "$p_{\text{succ DBO}}$", is given by:

In "words": $p_{\text{succ DBO}} =$

$$\frac{1}{n}\sum_{j=0}^{n}\left(\begin{array}{l} \Pr\{st=j/0\}.\Pr\{\text{GBS } \overline{\text{trm}} \wedge 1t_{\text{orig}} \text{ trm} \wedge \text{all } t_{\text{back}} \overline{\text{rtr}} \mid st=j/0\} + \\ \Pr\{st=j/0\}.\Pr\{\text{GBS } \overline{\text{trm}} \wedge \text{all } t_{\text{orig}} \overline{\text{trm}} \wedge 1t_{\text{back}} \text{ rtr} \mid st=j/0\} + \\ \Pr\{st=j/1\}.\Pr\{\text{GBS } \overline{\text{rtr}} \wedge 1t_{\text{orig}} \text{ trm} \wedge \text{all } t_{\text{back}} \overline{\text{rtr}} \mid st=j/1\} + \\ \Pr\{st=j/1\}.\Pr\{\text{GBS } \overline{\text{rtr}} \wedge \text{all } t_{\text{orig}} \overline{\text{trm}} \wedge 1t_{\text{back}} \text{ rtr} \mid st=j/1\} \end{array}\right)$$

This leads to the following formula :

$p_{\text{succ DBO}} =$

$$\frac{1}{n}\sum_{j=0}^{n}\left(\begin{array}{l} [\Pr\{st=j/0\}\times(1-p_{g0}) + \Pr\{st=j/1\}\times(1-p_g)]\times \\ [\text{bin}(1,n-j,p_{d0})\times(1-p_d)^{j} + (1-p_{d0})^{n-j}\times\text{bin}(1,j,p_d)] \end{array}\right) \tag{32}$$

To calculate the throughput of the DBO terminals we have to take into account that not all slots are available for DBO data.
Therefore the throughput of "n" DBO terminals can be calculated with:

$$p_{\mathrm{thr\ DBO}} = n \times p_{\mathrm{succ\ DBO}} \times p_{\mathrm{free}} \ . \qquad (33)$$

with:

$$p_{\mathrm{free}} = \frac{\mathrm{slpfr} - \mathrm{CTR_{sl}} - \mathrm{CBO_{sl}}}{\mathrm{slpfr}} \ . \qquad (34)$$

In this formula:

slpfr : Number of slots per frame.
CTR_{sl} : Number of slots in every frame assigned to CONTROL data.
CBO_{sl} : Number of slots assigned to CBO data, which is the result of formula 3.

The probability of a successful transmission by the GBS in a free slot "$p_{\mathrm{succ\ GBS}}$", is given by:

In words: $p_{\mathrm{succ\ GBS}}$ =

$$\sum_{j=0}^{n} \left(\begin{array}{l} \mathrm{Pr\{st=j/0\}.Pr\{GBS\ trm} \wedge \mathrm{all\,t_{orig}}\ \overline{\mathrm{trm}} \wedge \mathrm{all\ t_{back}}\ \overline{\mathrm{rtr}} \mid \mathrm{st=j/0\}} + \\ \mathrm{Pr\{st=j/1\}.Pr\{GBS\ rtr} \wedge \mathrm{all\,t_{orig}}\ \overline{\mathrm{trm}} \wedge \mathrm{all\ t_{back}}\ \overline{\mathrm{rtr}} \mid \mathrm{st=j/1\}} \end{array} \right)$$

This leads to the following formula :

$p_{\mathrm{succ\ GBS}}$ =

$$\sum_{j=0}^{n} [\mathrm{Pr\{st=j/0\}} \times p_{g0} + \mathrm{Pr\{st=j/1\}} \times p_g] \times (1-p_{d0})^{n-j} \times (1-p_d)^{j} \ . \qquad (35)$$

Taken into account that not all slots are available for DBO data, the throughput of the GBS can be calculated with:

$$p_{thr\ GBS} = p_{succ\ GBS} \times p_{free} \ . \tag{36}$$

The total system throughput can be calculated with:

$$syst_{thr} = \frac{CBO_{sl}}{slpfr} + p_{thr\ DBO} + p_{thr\ GBS} \ . \tag{37}$$

3.2.6 **The DBO packet delays.**

The DBO packet delay has to be calculated for both, packets transmitted by one of the DBO terminals ($t_{del\ DBO}$) and the GBS ($t_{del\ GBS}$).
On the average a new packet has to wait half a slot period before it is transmitted or rejected by a station. Next to that it takes one slot period to transmit the packet successfully.
When a packet collides after a transmission, it takes on the average "$1/p_d$" (or "$1/p_g$" for the GBS) free slot periods before a new transmission attempt is done. The average number of retransmissions done by a DBO terminal or the GBS are called "$nr_{rtr\ DBO}$" and "$nr_{rtr\ GBS}$" respectively .
Taken into account that when a slot is assigned for CBO traffic no transmission is done at all. In this case new packets are rejected and the age of the backlogged packets is increased with one slot period.
Therefore the average packet delays expressed in slot periods, each with a slot duration of T_{slot}, can be calculated with:

$$t_{del\ DBO} = 1.5 + \frac{nr_{rtr\ DBO}}{p_d \times p_{free}} \ , \qquad [\ T_{slot}\ ] \tag{38}$$

$$t_{del\ GBS} = 1.5 + \frac{nr_{rtr\ GBS}}{p_g \times p_{free}} \ . \qquad [\ T_{slot}\ ] \tag{39}$$

The number of retransmissions can be calculated with:

$$nr_{rtr\ DBO} = \frac{p_{transmit\ DBO}}{p_{succ\ DBO}} - 1 , \tag{40}$$

$$nr_{rtr\ GBS} = \frac{p_{transmit\ GBS}}{p_{succ\ GBS}} - 1 . \tag{41}$$

With:

$$p_{transmit\ DBO} = Pr\{DBO\ orig\} \times p_{d0} + Pr\{DBO\ back\} \times p_d , \tag{42}$$

$$p_{transmit\ GBS} = Pr\{GBS\ orig\} \times p_{g0} + Pr\{GBS\ back\} \times p_g . \tag{43}$$

With:

$$Pr\{DBO\ back\} = \frac{1}{n} \times \sum_{j=0}^{n} j \times [Pr\{st=j/0\} + Pr\{st=j/1\}] , \tag{44}$$

$$Pr\{DBO\ orig\} = 1 - Pr\{DBO\ back\} , \tag{45}$$

$$Pr\{GBS\ back\} = \sum_{j=0}^{n} Pr\{st=j/1\} , \tag{46}$$

$$Pr\{GBS\ orig\} = 1 - Pr\{GBS\ back\} . \tag{47}$$

4 THE SIMULATION MODEL.

For the simulation there are two different time scales. The first one is for the CBO traffic for which the average state transitions times are expressed in seconds or even minutes. The second one is for the DBO traffic, and the timescale is that of one slot duration, which is approximately a few hundred micro seconds.
To make a representative simulation on one timescale , it would take an enormous lot of time. For that reason the simulation is split in two separate simulations.
First the CBO traffic is simulated on a relative large timescale. When this is done the number of slots occupied by the CBO traffic can be determined. To this number, the number of CONTROL slots has to be added to find the number of slots not available for DBO traffic.
The total of CONTROL and CBO slots are randomly distributed over one frame. The remaining slots can be accessed by one of the DBO terminals or by the GBS for the transmission of a DBO data packet. In figure 10 a possible frame structure is depicted.

OCC BY CBO	FREE FOR DBO	OCC BY CTR	FREE FOR DBO	FREE FOR DBO	OCC BY CBO		FREE FOR DBO	OCC BY CBO	FREE FOR DBO	FREE FOR DBO
1	2	3	4	5	6		27	28	29	30

Figure 10 : Possible frame structure, assuming a frame length of 30 slots. (OCC = occupied; CTR = CONTROL data)

The results of the CBO simulation are used in the DBO simulation. Arrays with frame structures, like the one shown in figure 10, are used as an interface between both simulations.
Discrete time simulation is chosen for the simulation of both traffic types.

4.1 The simulation model for the CBO traffic.

In chapter 1 some remarks were made about the characteristic aspects of speech traffic. First a model for a speech conversation will be discussed here. A more detailed model for speech traffic can be found in [14] and [15].

If we look at a CBO terminal which produces speech traffic, it can be in three different states. See figure 11. The first one is "no connection" (NO CONN). The second one is having a connection and being in a silent period (CONN SLNT). The third one is having a connection and being in a talkspurt period (CONN TALK).

In the state "NO CONN" it is assumed equally likely to go to the state "CONN SLNT" or to the state "CONN TALK". This is why p1 has to be multiplied with ½.

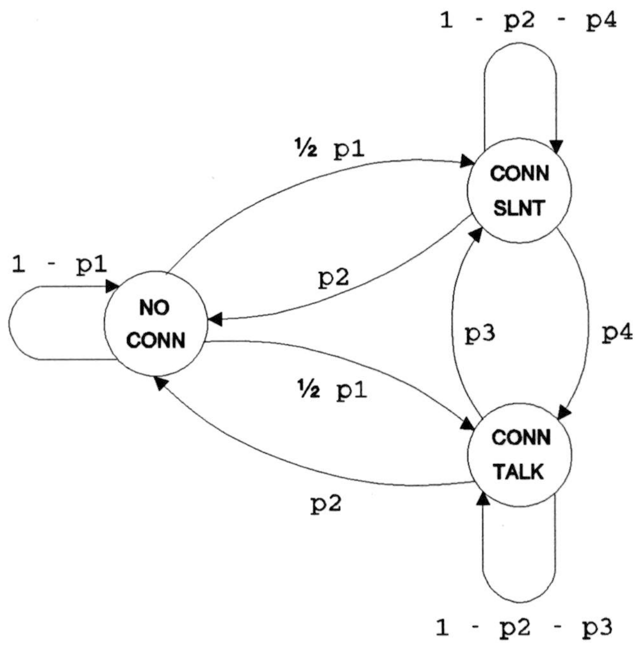

Figure 11 : State transition diagram for a CBO speech terminal.

Because a discrete time simulation has been chosen, the duration of one simulation period has to be determined. When this is chosen too small the simulation would be very time consuming. When it is chosen too large the probability that a terminal will have two transitions in one simulation period cannot be neglected.

The fastest transitions of a CBO terminal occur between the states "CONN SLNT" and "CONN TALK", and take place about every second, according to section 3.1. For this reason the simulation period, called "τ_{sim}", is chosen to be 0.1 sec. In this case the probability of two transitions during one simulation run is less than 1 % and therefore is neglected.

To calculate the transition probabilities in one simulation period the following parameters have to be known:

λ_c : CBO call arrival rate for every free CBO source [hour^{-1}].
t_{c_hld} : CBO call holding time [min].
τ_{sim} : Simulation interval time (0.1 sec).
τ_{talk} : Average talkspurt period. (1 sec).
τ_{slnt} : Average silent period. (1,35 sec).

As already mentioned in section 3.1 the parameters λ_c and $\mu_c = 1/t_{c\_hld}$ used in the ENGSET model are exponentially distributed. According to [12] and [16] this is also the case for τ_{talk} and τ_{slnt}. Therefore the transition probabilities p1..p4 can now be calculated with:

$$p_i = 1 - e^{-\alpha_i} . \qquad i = 1, 2, 3, 4 \qquad \textbf{(48)}$$

with:

$$\alpha_1 = \frac{\lambda_c \times \tau_{sim}}{3600} ; \quad \alpha_2 = \frac{\tau_{sim}}{60 \times t_{c\_hld}} ; \quad \alpha_3 = \frac{\tau_{sim}}{\tau_{talk}} ; \quad \alpha_4 = \frac{\tau_{sim}}{\tau_{slnt}} . \qquad \textbf{(49)}$$

There are two more points, regarding the simulation of the CBO traffic.

i) All CBO terminals have a duplex connection. So they not only produce speech packets, but they also receive speech packets, coming from the remote CBO terminal and transmitted by the GBS. In fact the transition diagram of figure 11 should be extended, so the state of the remote CBO terminal and the interaction between the two CBO terminals are described as well.
No data has been found in literature, which describes the interaction between two communicating telephone users. Therefore for simplicity both CBO terminals are considered to be independent

in this study. Each having its own state transition conform fig. 11. It is not expected a big error is made with this assumption, because the fraction of occupied slots will not change.
With this assumption, and the fact that there are "m" CBO terminals in the group, "2m" individual terminals have to be simulated, to determine the number of occupied slots by the CBO traffic. The second "m" terminals are represented in the GBS.

ii) As described in section 3.1 there is a maximum number "k" of CBO circuits. This number "k" can be determined with the recursive procedure described by the formulas 4..7 .
If "k" out of "2m" terminals are in the state "CONN TALK" or in the state "CONN SLNT", other CBO terminals which are in the state "NO CONN" are forbidden to leave this state.

For the simulation of the CBO traffic, the flow diagram shown in figure 12 has been implemented. In this simulation the number of CBO terminals, which are in the state "CONN TALK", "CONN SLNT" or "NO CONN", are updated at the end of every run. These numbers are nr_talk, nr_slnt and nr_ncon respectively. During the simulation run the variation of these numbers are kept up with Δnr_talk, Δnr_slnt and Δnr_ncon, respectively.

The function **prob(x)** used in this figure returns "TRUE" with probability "x" and "FALSE" with probability "1-x". The function **decr(y)** decrements, and the function **incr(y)** increments the value of y with one.

Notice that with this implementation small errors for p3, p4 and ½p1 are introduced, because they are multiplied with (1-p2), (1-p2) and (1-½p1) respectively. Because p2 and ½p1 have very small values, this error can be neglected.

Only terminals, which are in the state "CONN TALK" occupy a slot in the momentary frame. So after every simulation run the number of slots assigned to CBO traffic in one frame, can be determined with:

$$CBO_{sl} = nr\_talk \; . \tag{50}$$

During CBO simulations the number of occupied slots (CBO_{sl} + CTR_{sl}) is determined. The occupied slots are randomly distributed over the frame, like the one shown in figure 10. This new frame structure is written to a file. When simulating the DBO traffic these frame structures are read from this file.

To make a good comparison between the analytical and the simulation model possible, the CBO traffic has to be averaged over a long period of time. Subsequent CBO simulation runs will show slowly varying number of occupied slots per frame. For the average value the CBO traffic it is therefore not necessary to update the CBO throughput after every simulation run. For this reason new frame structures are produced and written to the file with a periodicity of about twenty CBO simulation runs. This will restrict the size of the file with frame structures.

4.2 The simulation model for the DBO traffic.

Before simulating the DBO traffic, first the number of slots occupied by the CBO traffic and the CONTROL data, and their location in the frame have to be determined. For this reason every "slpfr" DBO simulations a new frame structure, like the one shown in figure 10, is read from the file produced during the CBO simulation (slpfr = number of slots per frame).

In subsection 3.2.1 the state transition diagram of a single terminal is discussed. At the beginning of a slot period the terminal can only be in the state originating (ORIG) or in the state backlogged (BACK).

For the implementation of the DBO simulation model an array with a record for each DBO terminal and the GBS is updated for every slot period. In these records the state of the terminal (ORIG or BACK) and the age of a backlogged packet (AGE_COUNT) is stored.

Figure 13 shows the flow diagram of the DBO traffic simulation during one slot period. In this figure a station could be either one of the DBO terminals or the GBS.

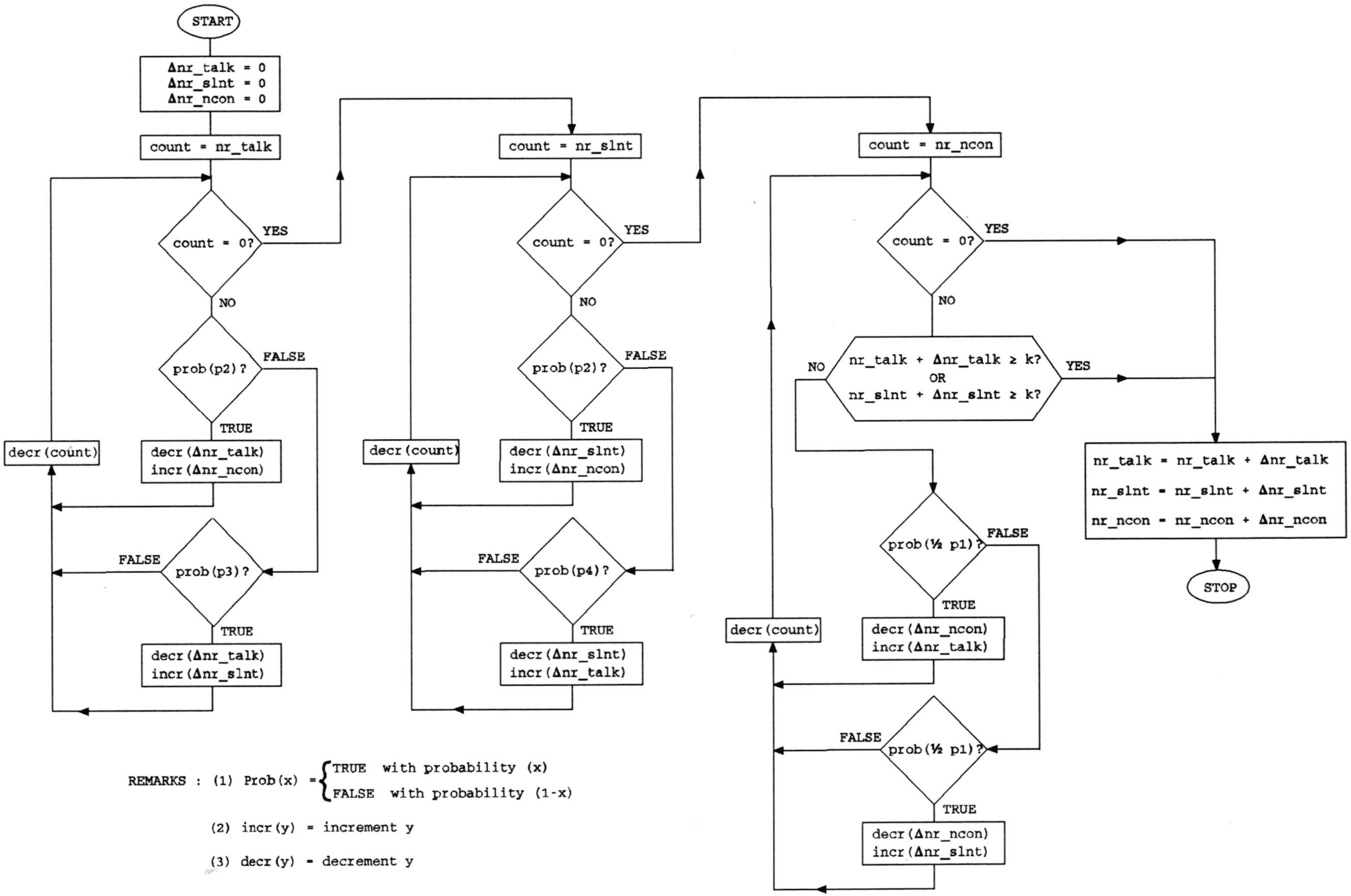

Figure 12 : Procedure of one CBO traffic simulation run.

Some remarks regarding the activity "SIMULATE THE TRANSMISSION ATTEMPTS OF ALL STATIONS" are:

- If a DBO terminal is in originating mode, it transmits with probability p_{d0}, else when it is backlogged it retransmits with probability p_d. For the GBS these probabilities are p_{g0} and p_g respectively.
- The AGE_COUNT of a newly arrived packet is set to 1,5. This is "0,5" for the average waiting time and "1" for the transmission in the first free slot.

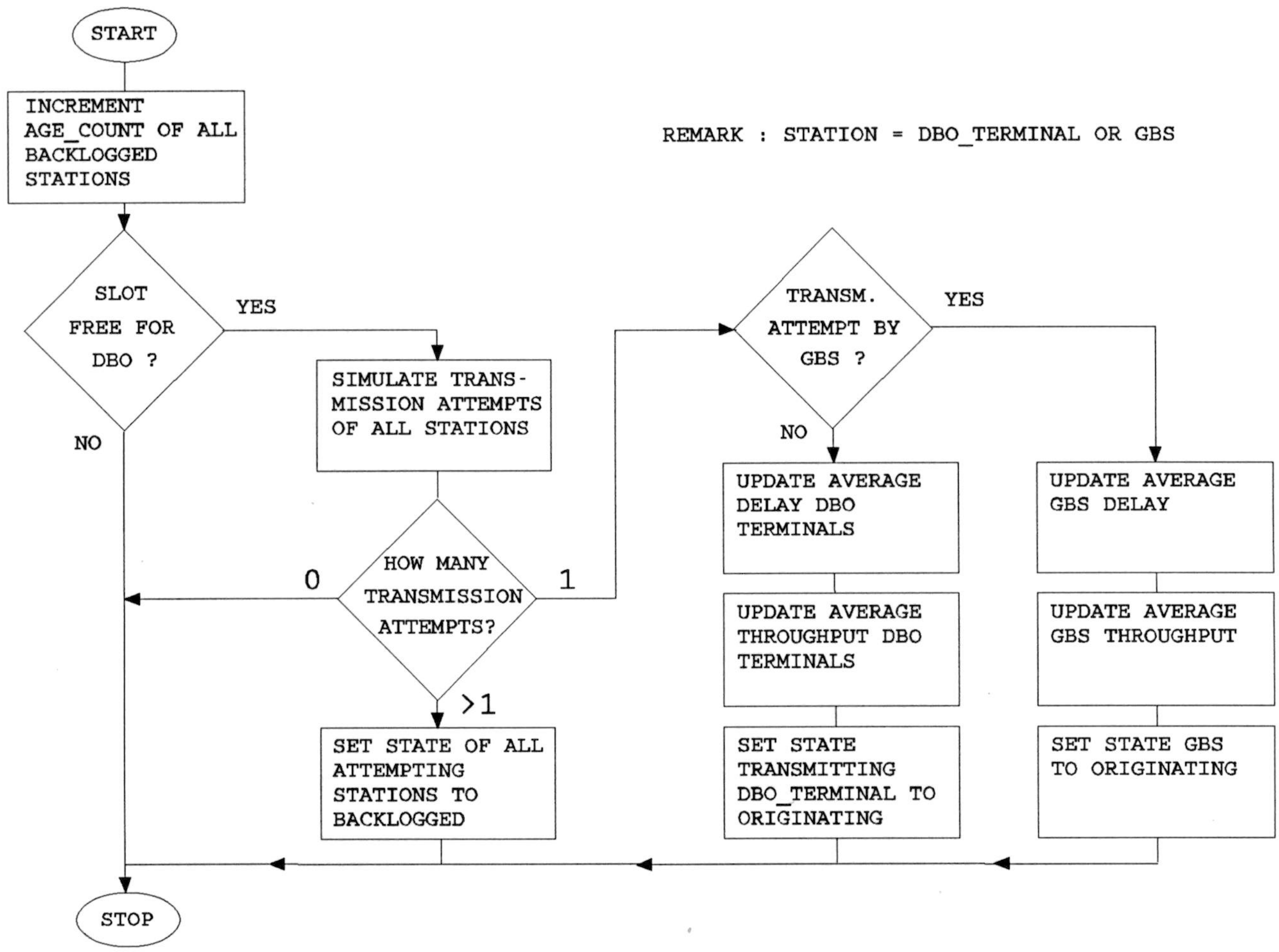

Figure 13 : DBO traffic simulation procedure for every slot period.

5 RESULTS OF ANALYSIS AND SIMULATIONS.

In this chapter the results of the analysis are given. These are compared with the results of the simulation models for validation. In the first section this is done for the CBO traffic. In the second section this is done for a system with an integration of the CBO and the DBO traffic.

5.1 Validation of the model for CBO traffic.

If we look at the analytical model of the CBO traffic in section 4.1, there are four variables, which can be distinguished, viz:

i)	Number of CBO terminals.	(nr_{CBO})
ii)	Call arrival rate for free CBO source [$hour^{-1}$].	(λ_c)
iii)	Call holding time [min].	($t_{c\_hld} = 1/\mu_c$)
iv)	Blocking probability.	(p_{bl})

For each of these variables three different values are considered. The results for the CBO traffic of both the analytical and the simulation model are given in the figures 14..17.
Ten simulation runs are done for every figure. Every run corresponds with about three hours of CBO traffic for the figures 14..16 and about 12 hours of CBO traffic for figure 17.
In the figures 14..16 the solid lines are the results of the analytical model and the stars, diamonds and triangles are the result of the simulation model. From these figures it can be concluded that the simulation model matches the analytical model for the variation of nr_{CBO}, λ_c and t_{c_hld}.
In figure 17 the straight lines are the results of the analytical model and the fluctuating lines connect the results of the simulation runs. Notice that a different scaling is used for the CBO throughput in this plot. From this figure it can not be concluded that both models match. However the average values of the CBO throughput for the simulation runs in this plot, decrease with an increasing blocking probability. This is also the case for the results of the analytical model.

Given these results it is assumed that the CBO traffic stream can correctly be described by the analytical model presented in section 3.1

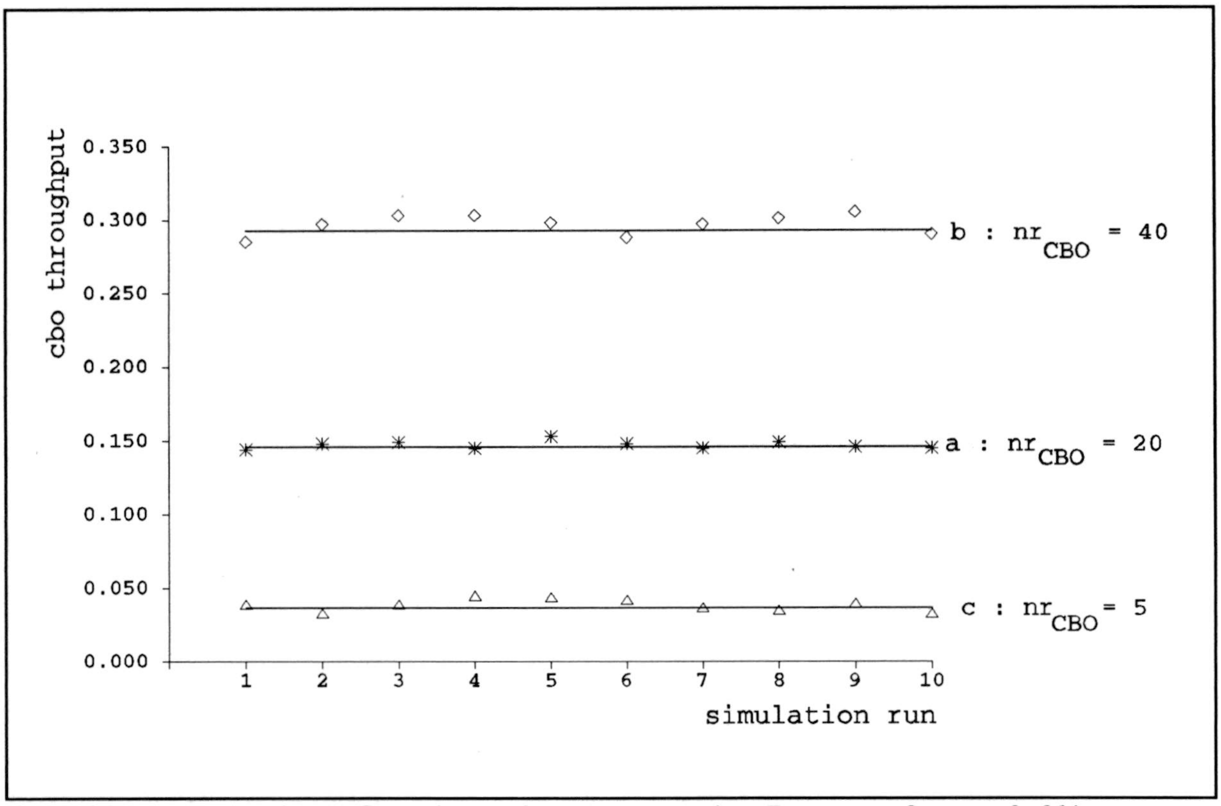

Fig. 14 : Variation of number of CBO users (λ_c=7; t_{c_hld}=3; p_{bl}=0.01). Analysis result of formula 3 ;Simulations result of formula 50.

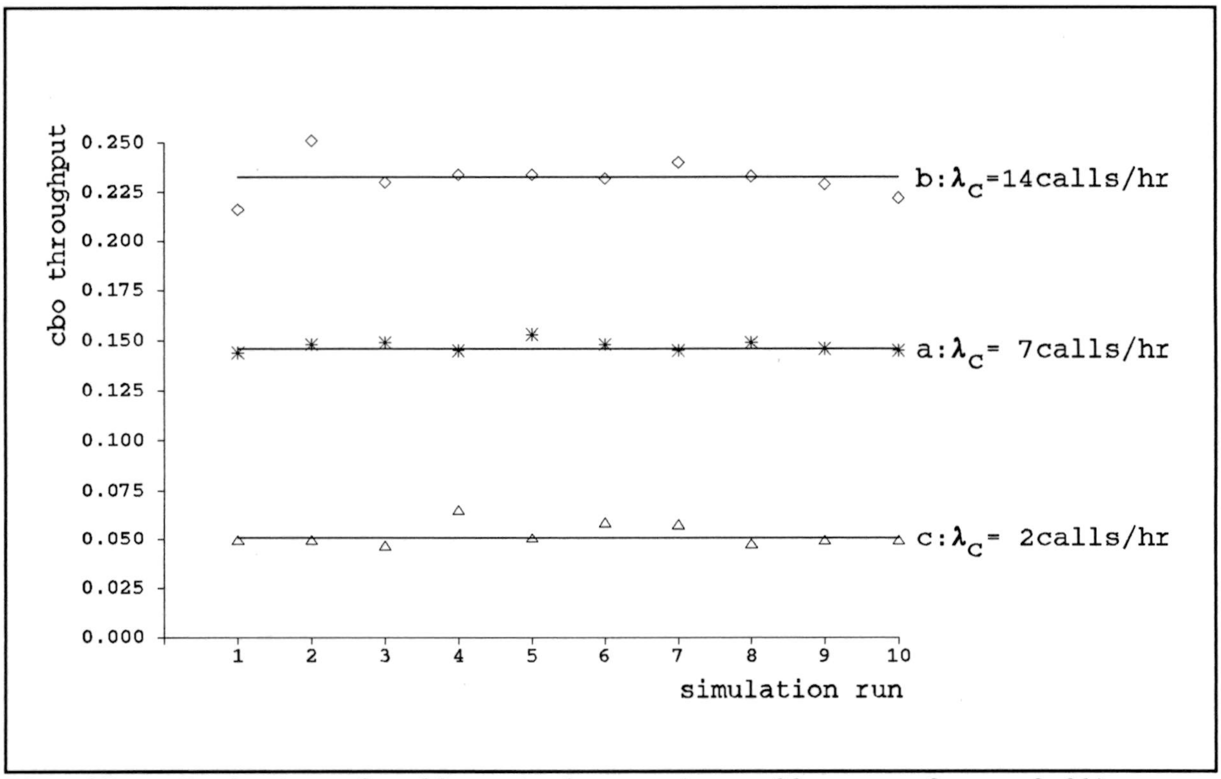

Fig. 15 : Variation of call arrival rate (nr_{CBO}=20; t_{c_hld}=3; p_{bl}=0.01). Analysis result of formula 3; Simulations result of formula 50.

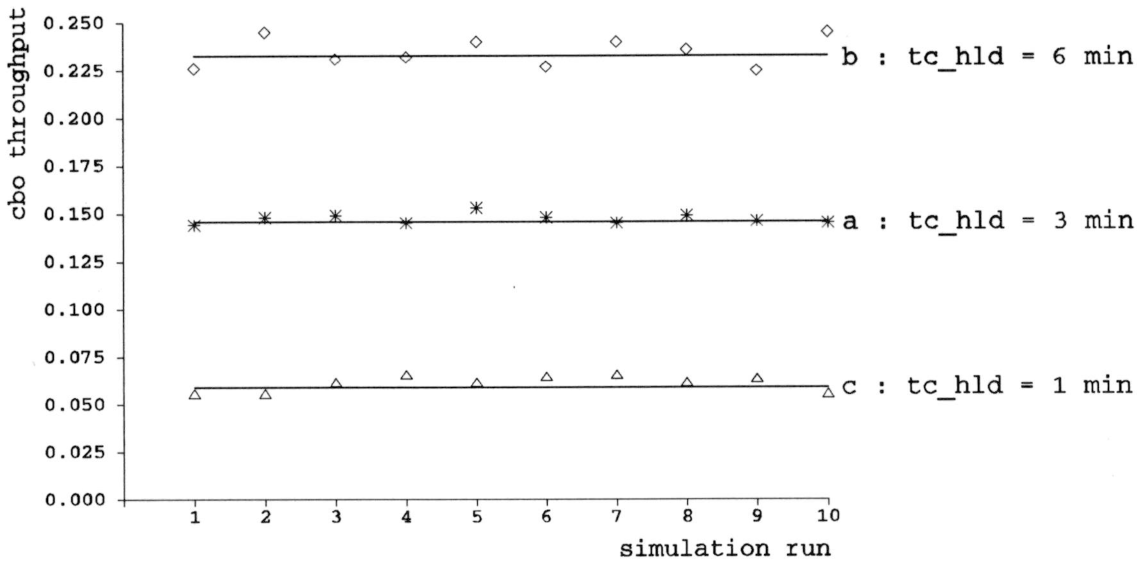

Fig. 16 : Variation of call holding time (nr_{CBO}=20; λ_c=7; p_{bl}=0.01). Analysis result of formula 3; Simulations result of formula 50.

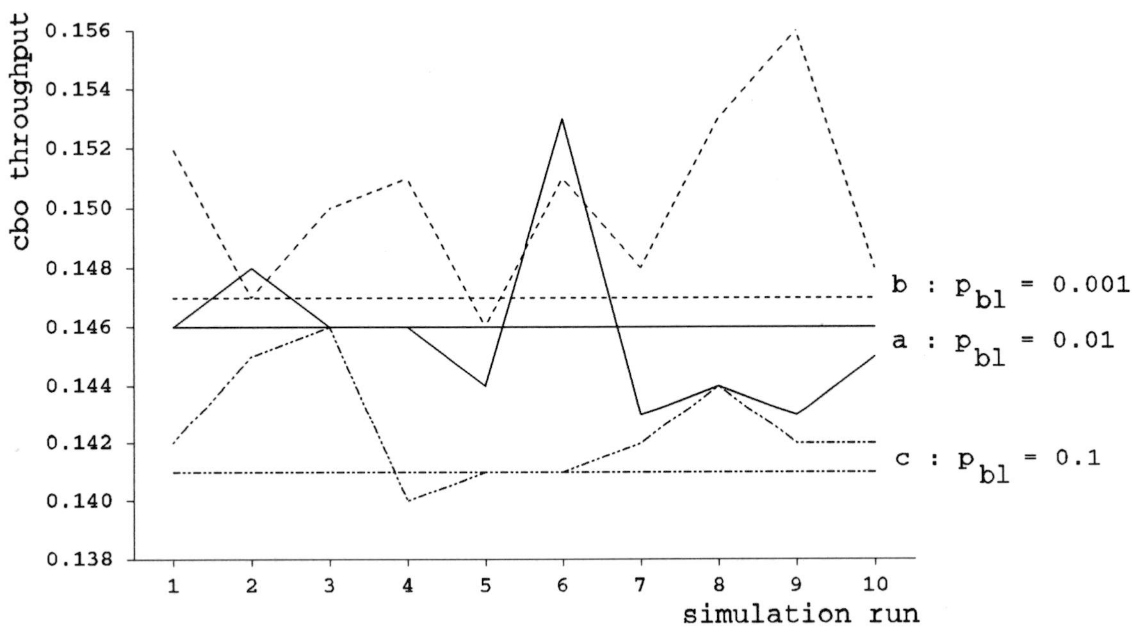

Fig. 17 : Variation of blocking probability (nr_{CBO}=20; λ_c=7; t_{c_hld}=3). Analysis result of formula 3; Simulations result of formula 50.

5.2 The results of integrated CBO and DBO traffic.

In figure 18 – 47 the results of the combined CBO and DBO analysis and simulations are shown. There are five variables considered. The variables are:

cbothr : The CBO throughput
(For the CBO traffic itself, there are more variables as mentioned in the former section. The only important item for the link performance is however the fraction of the system capacity which is assigned to this CBO traffic.)

nr_{DBO} : The number of DBO terminals.

inb_outb : The ratio between inbound and outbound DBO packet arrivals.

p_d : The probability of retransmitting a backlogged DBO packet in a free slot by a DBO terminal.

p_g : The probability of retransmitting a backlogged DBO packet in a free slot by the GBS.

For three different values of every variable the throughput and delay versus the packet arrival rate per slot period are depicted. In this way the influence of every variable on the performance of the CRMA link is shown.

At the horizontal axes of every plot the DBO packet arrival rate in one slot period, anywhere in the group, is marked out. With formula 10 and formula 13, the packet arrival rate for a single DBO terminal or the GBS can be calculated respectively.

For every system two plots are given, viz. for the throughput and for the delay. In the throughput diagram the fraction of the total link capacity used for CBO traffic (CBO), DBO traffic by all group terminals (DBO), DBO traffic by the GBS (GBS) and the total link utilisation (total) are marked out. In the delay plot the average delay for a DBO packet transmitted by the DBO terminals (DBO) and the GBS (GBS) are marked out. The solid lines are the results of the analysis, and the stars, triangles (upwards and downwards) and the circles mark the result of the simulations.

If we look at the results of the analysis and the simulation of all plots, it points out that both models match very well. Therefore it is assumed that the results of the analytical model can be used for evaluating the CRMA protocol.
All plots will be discussed hereafter, to find out what the behaviour of the CRMA link performance is, for different values of the above mentioned variables.
For all evaluated systems, frame sizes of 30 slots (slpfr = 30) are considered, and the number of CONTROL slots is stated to be zero. (See the formulas 34 and 36 and figure 10). If CONTROL slots are taken into account, these have an equal effect on the DBO traffic transport as the CBO traffic.

The figures 18 - 23 show how the system reacts when only the level of CBO traffic changes.
As can be seen from these plots, with higher CBO traffic the total link utilisation increases, but the DBO and GBS throughput will decrease. These DBO and GBS throughput appear to be the same fraction of the remaining capacity, after the CBO portion has been subtracted from the link capacity. The packet delay will increase at higher CBO traffic loads with a factor: [1/(1-cbothr)] , because more slots are occupied by CBO data, and therefore the DBO transmission more frequently has to be rescheduled.

The figures 18 and 19 depict the throughput and delay if there is no CBO traffic at all. The maximum throughput appears to be about 37% of the link capacity. Because of the chosen inb_outb ratio of "2", there is more DBO traffic produced by the group DBO terminals than by the GBS.
At higher traffic loads more collisions occur, which can be concluded from the increasing packet delays. As a result the throughput will decrease.

From the delay plots it can be concluded that even when the number of collisions increase the packet delays for the DBO terminals as well as for the GBS are very low.

A CBO throughput of 15%, like the system shown in the figures 20 and 21, is realised with the following CBO traffic parameters: $nr_{CBO}=20$; $\lambda_c=7$; $t_{c\_hld}=3$; $p_{bl} = 0.01$. A CBO throughput of 34%, like the system of figures 22 and 23 is realised with: $nr_{CBO}=30$; $\lambda_c=10$; $t_{c\_hld}=4$; $p_{bl} = 0.01$.

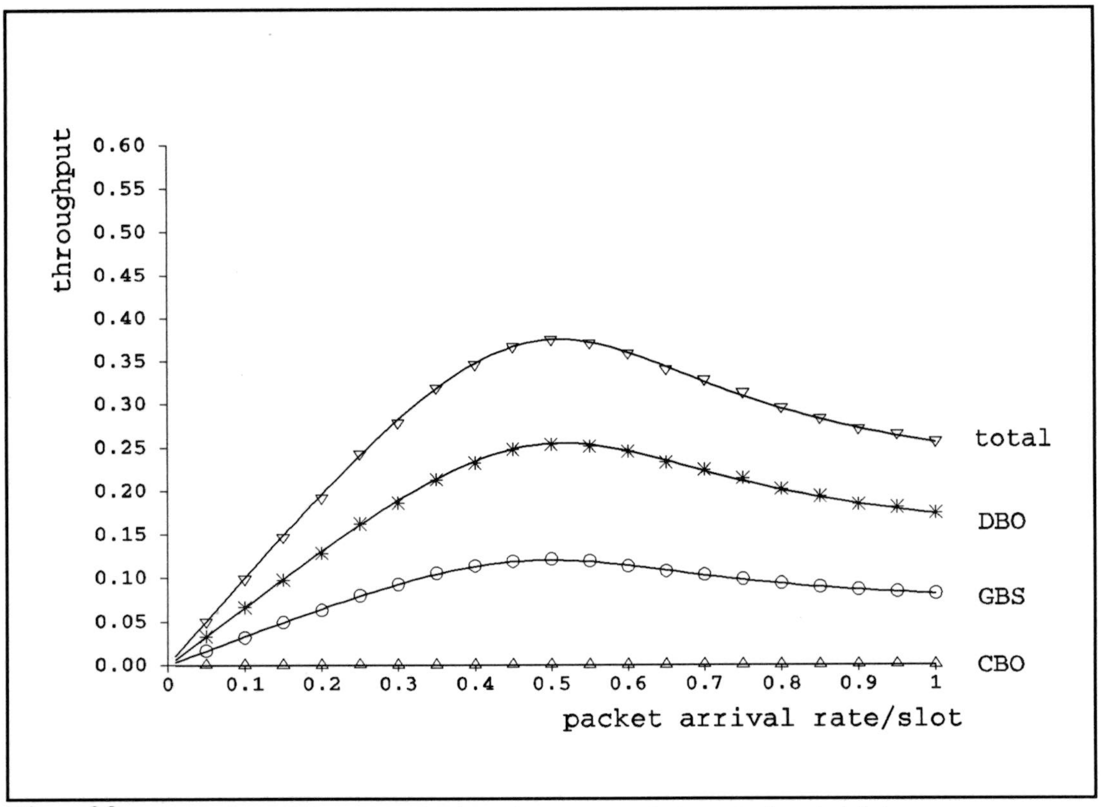

Fig. 18: CBO,DBO, GBS and total throughput vs. packet arrival rate/slot,
for: nrDBO=20; inb_outb=2; pd=0.1; pg=0.5; **cbothr=0.00**.

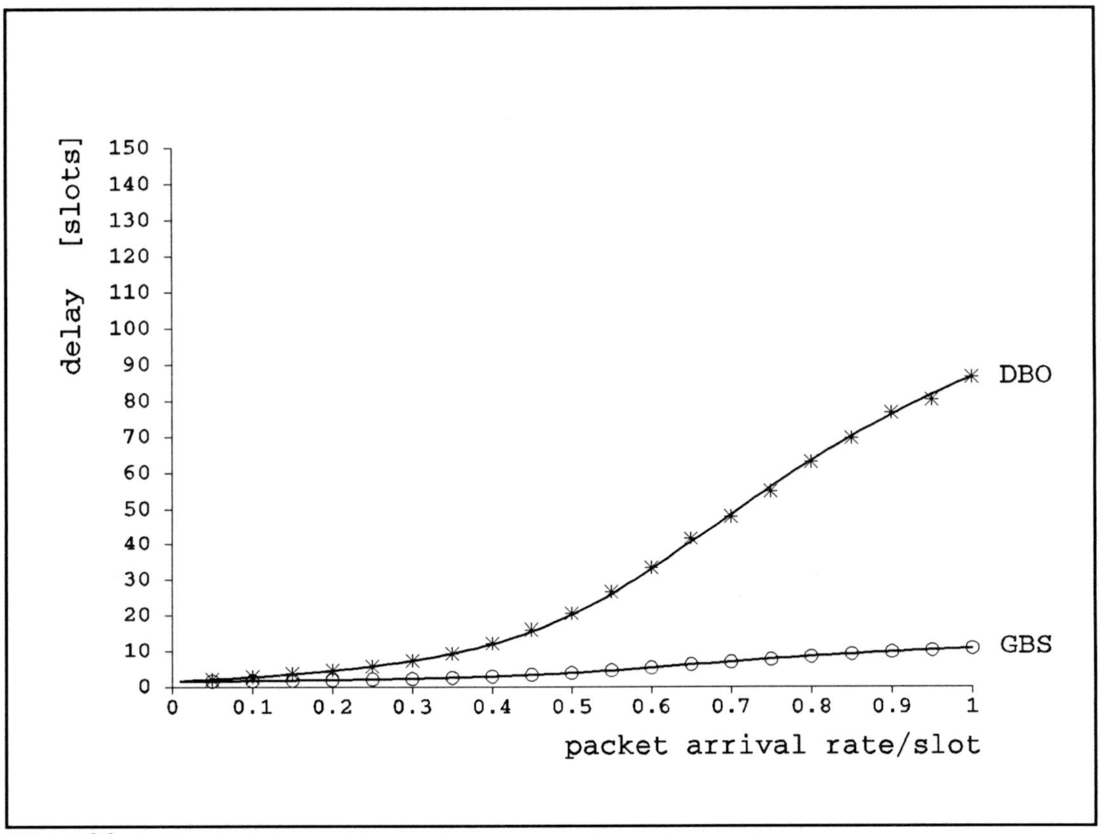

Fig. 19: DBO and GBS packet delay vs. packet arrival rate/slot,
for: nrDBO=20; inb_outb=2; pd=0.1; pg=0.5; **cbothr=0.00**.

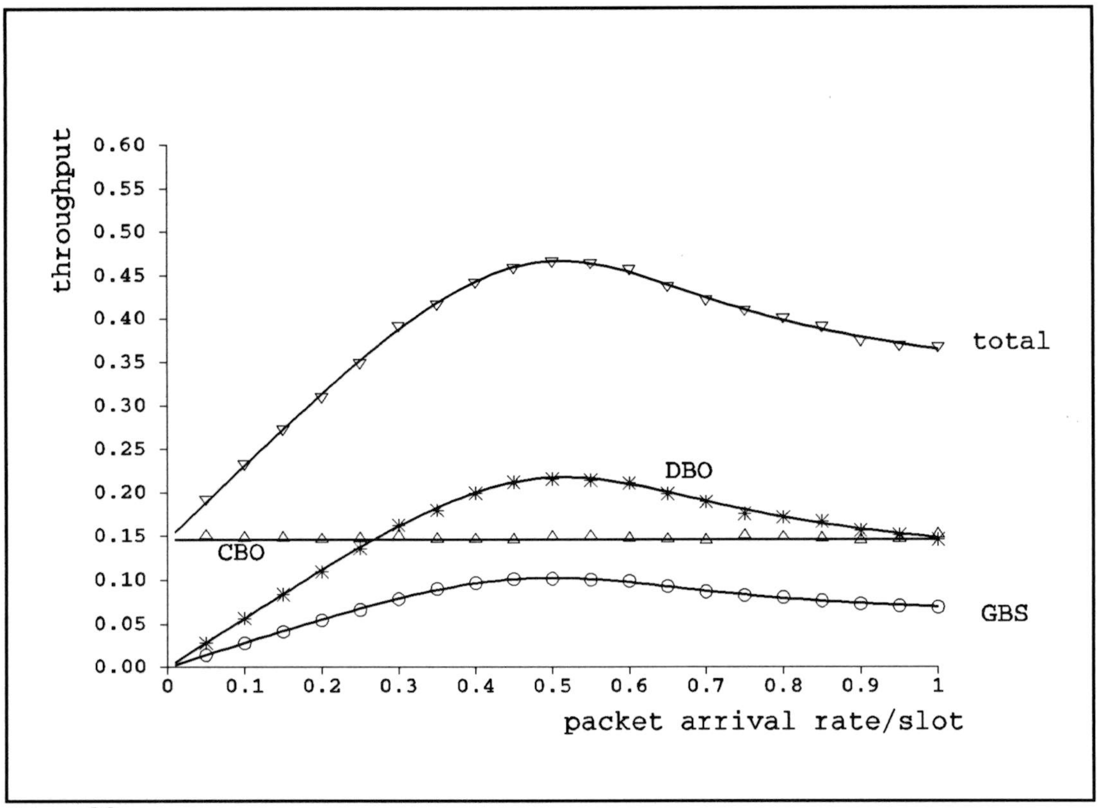

Fig. 20: CBO,DBO, GBS and total throughput vs. packet arrival rate/slot, for: nrDBO=20; inb_outb=2; pd=0.1; pg=0.5; **cbothr=0.15**.

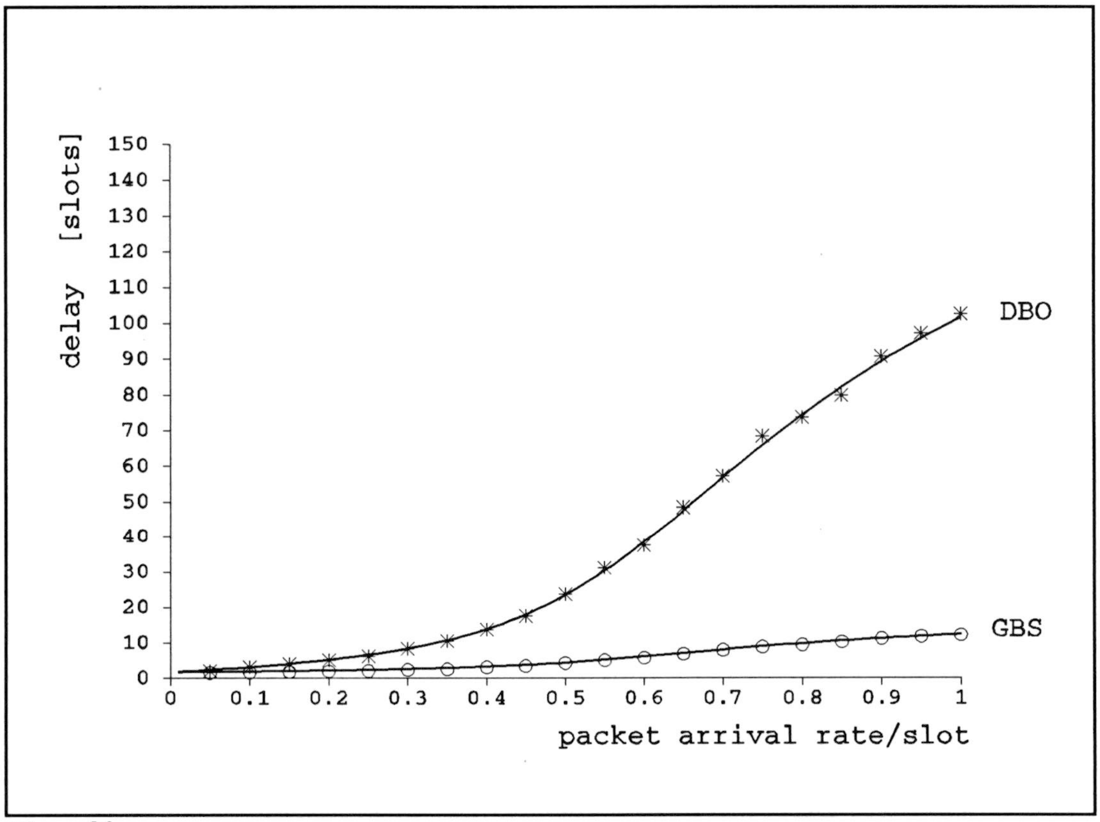

Fig. 21: DBO and GBS packet delay vs. packet arrival rate/slot, for: nrDBO=20; inb_outb=2; pd=0.1; pg=0.5; **cbothr=0.15**.

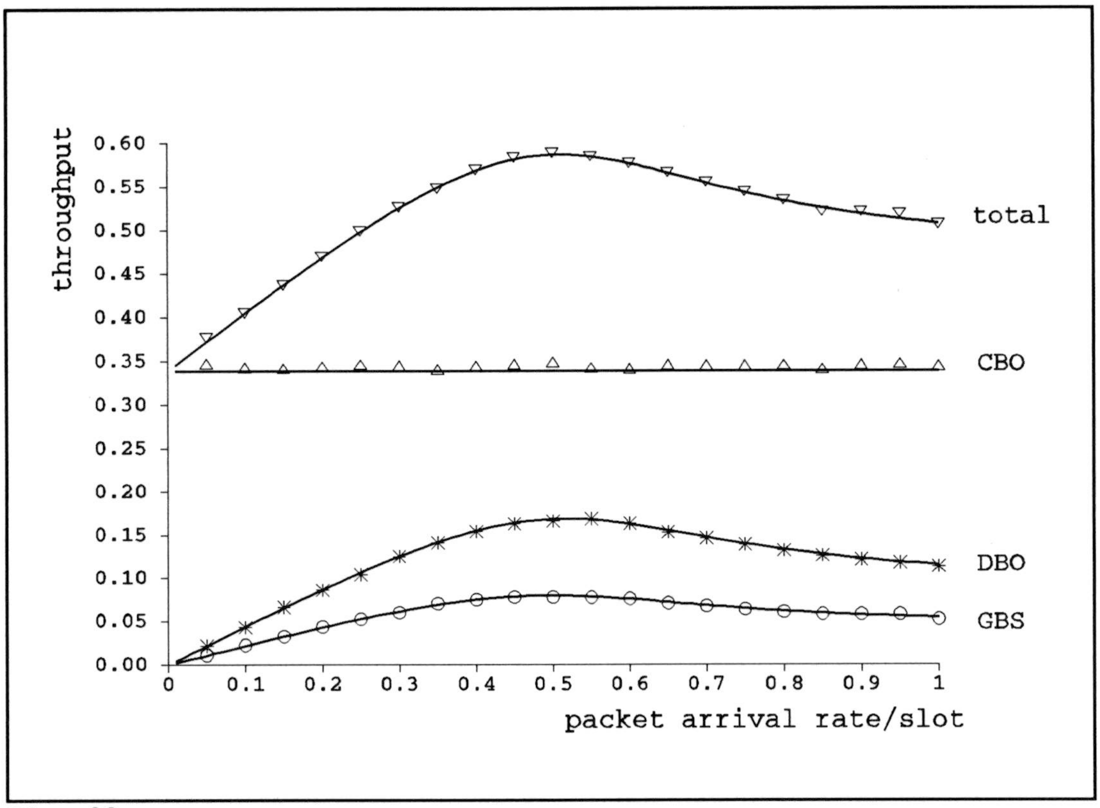

Fig. 22: CBO,DBO, GBS and total throughput vs. packet arrival rate/slot,
for: nrDBO=20; inb_outb=2; pd=0.1; pg=0.5; **cbothr=0.34**.

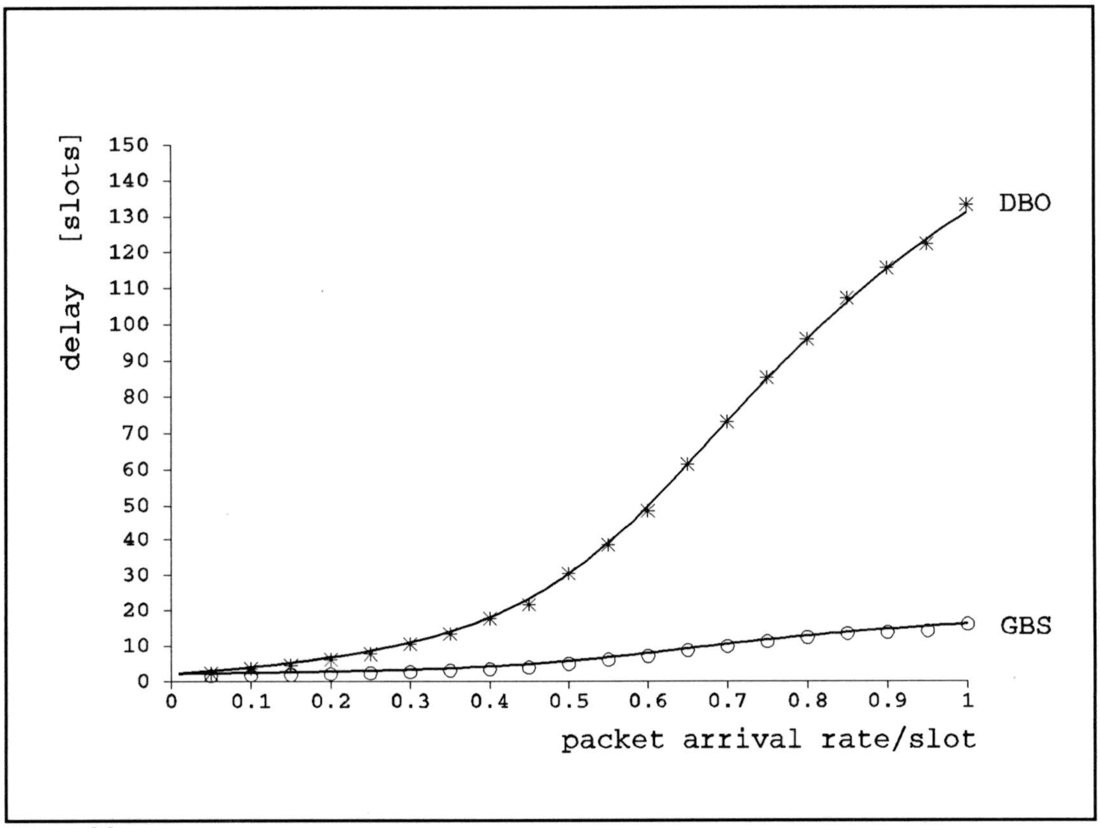

Fig. 23: DBO and GBS delay vs. packet arrival rate/slot,
for: nrDBO=20; inb_outb=2; pd=0.1; pg=0.5; **cbothr=0.34**.

Figures 24 - 29 give an indication of the system performance, when the ratio between the inbound and outbound traffic arrival rates varies.

From these graphs it can be calculated that from the remaining capacity left unused by the CBO traffic, the utilisation for the DBO traffic can vary between about 37 % and 60%. The lower value is valid if there are a lot of bursty users, and the higher throughput can be reached when the main traffic stream is produced by the GBS.

The system shown in figure 24 and 25 transports almost only inbound traffic, i.e. traffic produced by the group DBO terminals.
Figure 26 and 27 show the result of a system, with as much inbound as outbound traffic. The system of figure 28 an 29 mostly transports packets produced by the GBS.

It appears that the more of the total traffic stream is produced by the GBS, the higher the total throughput can be. For an inb_outb ratio of 10, 1 and 0.1 the maximum link utilisation can be 46%, 48% and 65% respectively. This is as could be expected because packets transmitted by the GBS, are placed in different timeslots, and therefore will not collide with each other.

With an inb_outb ratio of 10 there is not one big stream produced by the GBS, with a high transmission probability. In this case the DBO terminals are more likely to find a free slot, and therefore are less frequently backlogged, than with an inb_outb ratio of 1. The maximum packet delays for the DBO terminals in these cases are 82 and 95 slots respectively. The GBS however suffers a maximum packet delay of 14 slots when inb_outb = 10 and 10 slots when inb_outb = 1. This is caused by the higher transmission rate for the DBO terminals in figure 25, the GBS will more frequently suffer a collision, than in the system of figure 27, and therefore has a higher backlog probability.

It can be concluded from the figures 28 and 29, that with an inb_outb ratio of 0.1 little collisions occur, even at higher traffic rates, because there is only a little increase of the delay curves. This results in the high link utilization of 65 %.

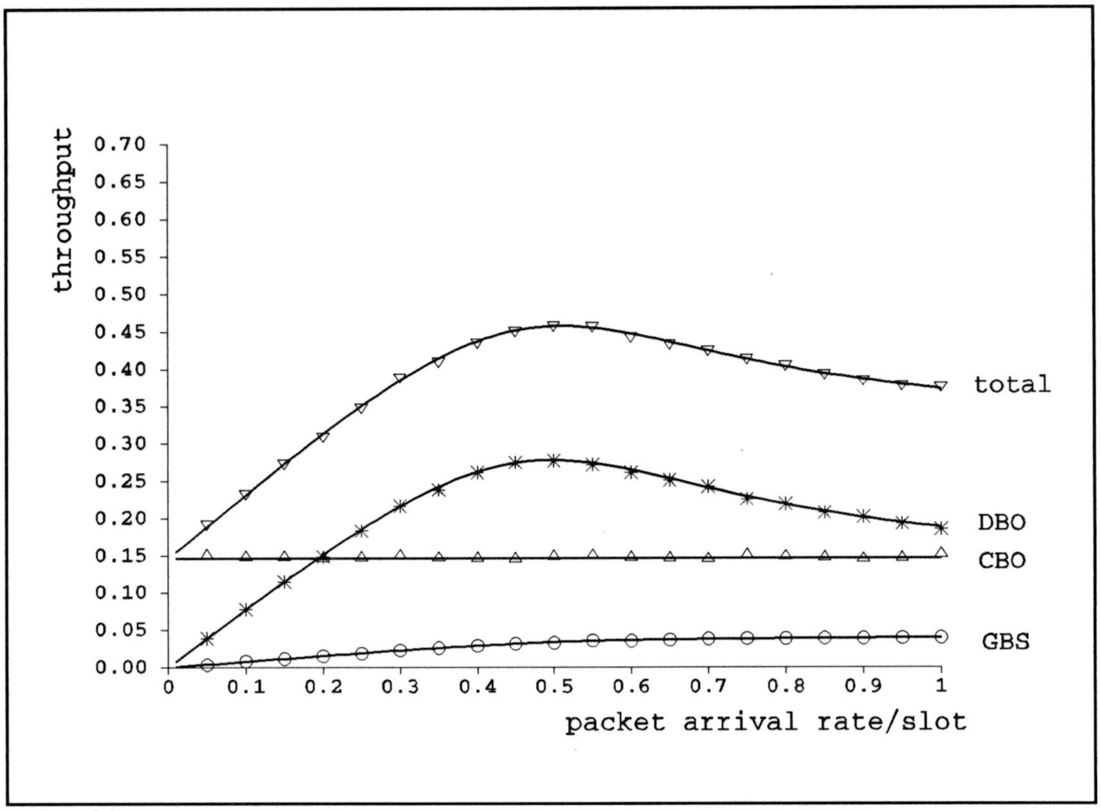

Fig. 24: CBO,DBO, GBS and total throughput vs. packet arrival rate/slot, for: nrDBO=20; **inb_outb=10**; pd=0,1; pg=0,5; cbothr=0,15.

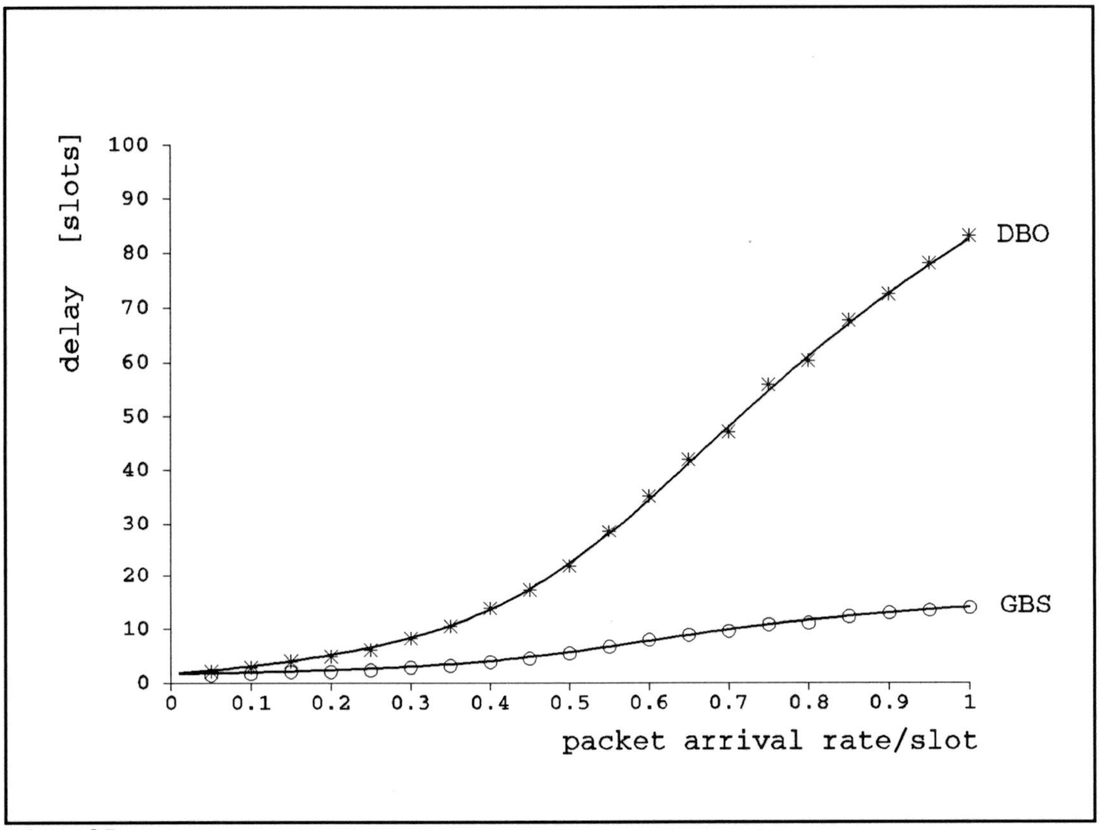

Fig. 25: DBO and GBS packet delay vs. packet arrival rate/slot, for: nrDBO=20; **inb_outb=10**; pd=0,1; pg=0,5; cbothr=0,15.

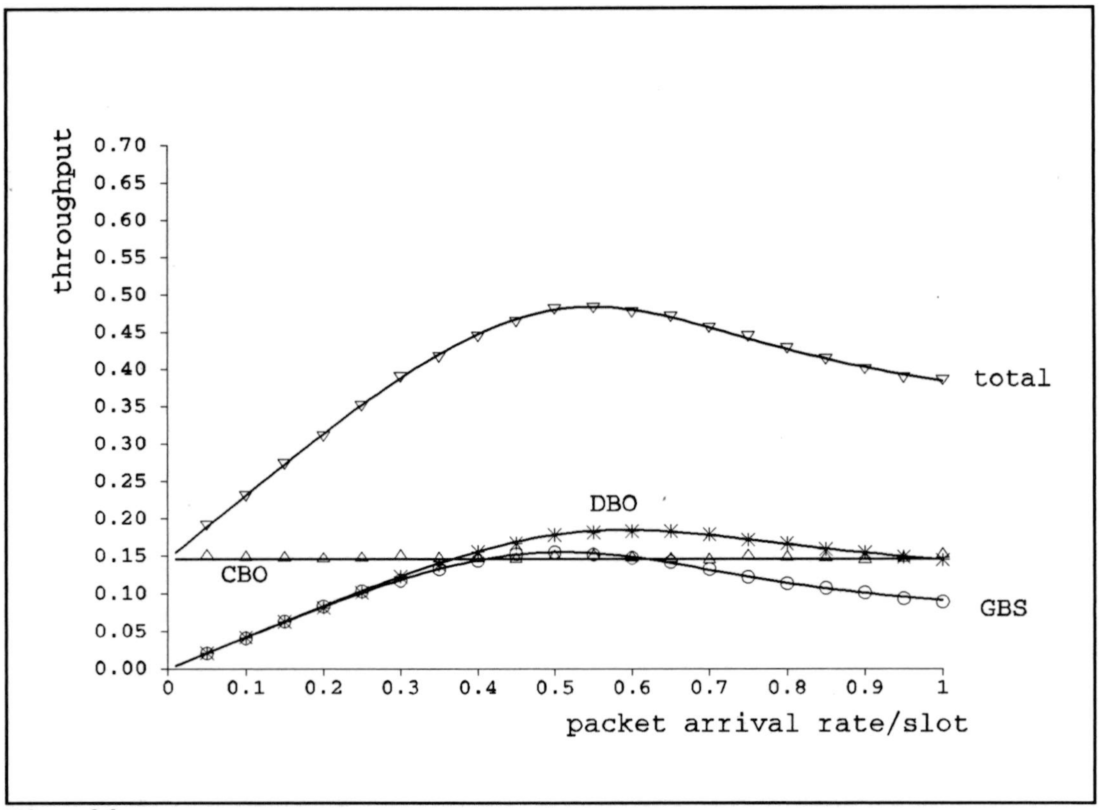

Fig. 26: CBO,DBO, GBS and total throughput vs. packet arrival rate/slot, for: nrDBO=20; **inb_outb=1**; pd=0.1; pg=0.5; cbothr=0.15.

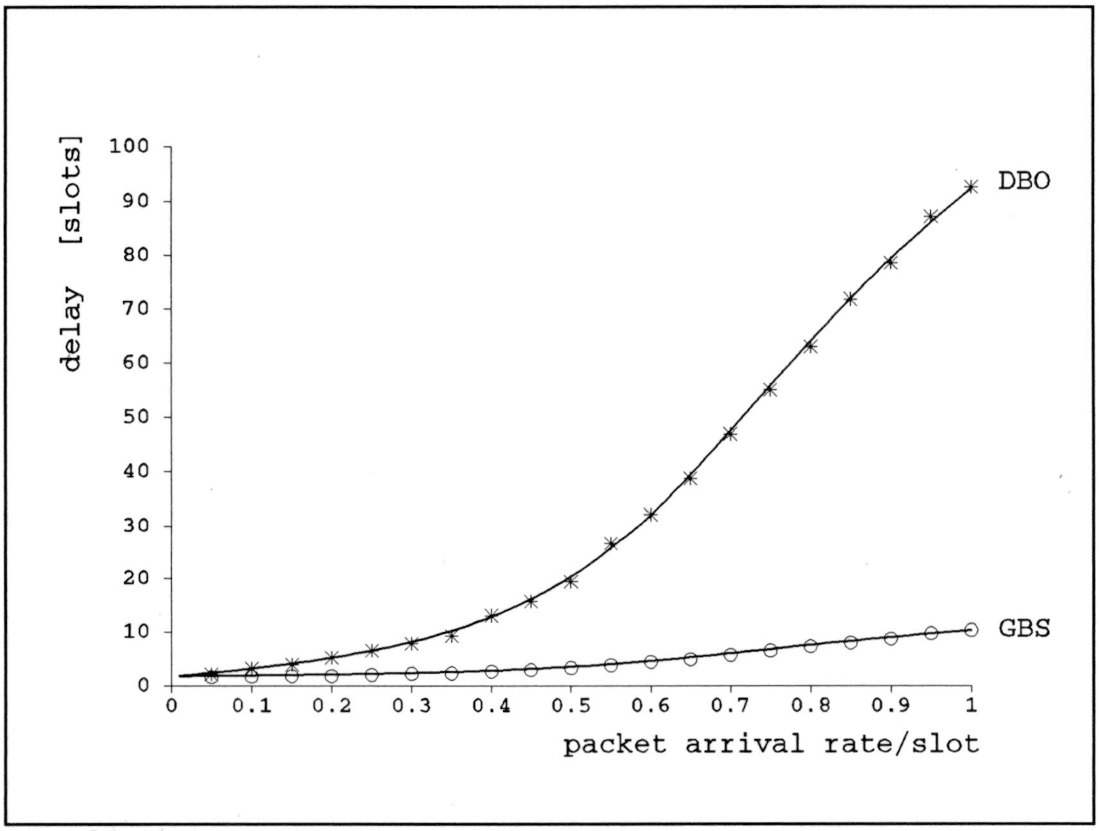

Fig. 27: DBO and GBS packet delay vs. packet arrival rate/slot, for: nrDBO=20; **inb_outb=1**; pd=0.1; pg=0.5; cbothr=0.15.

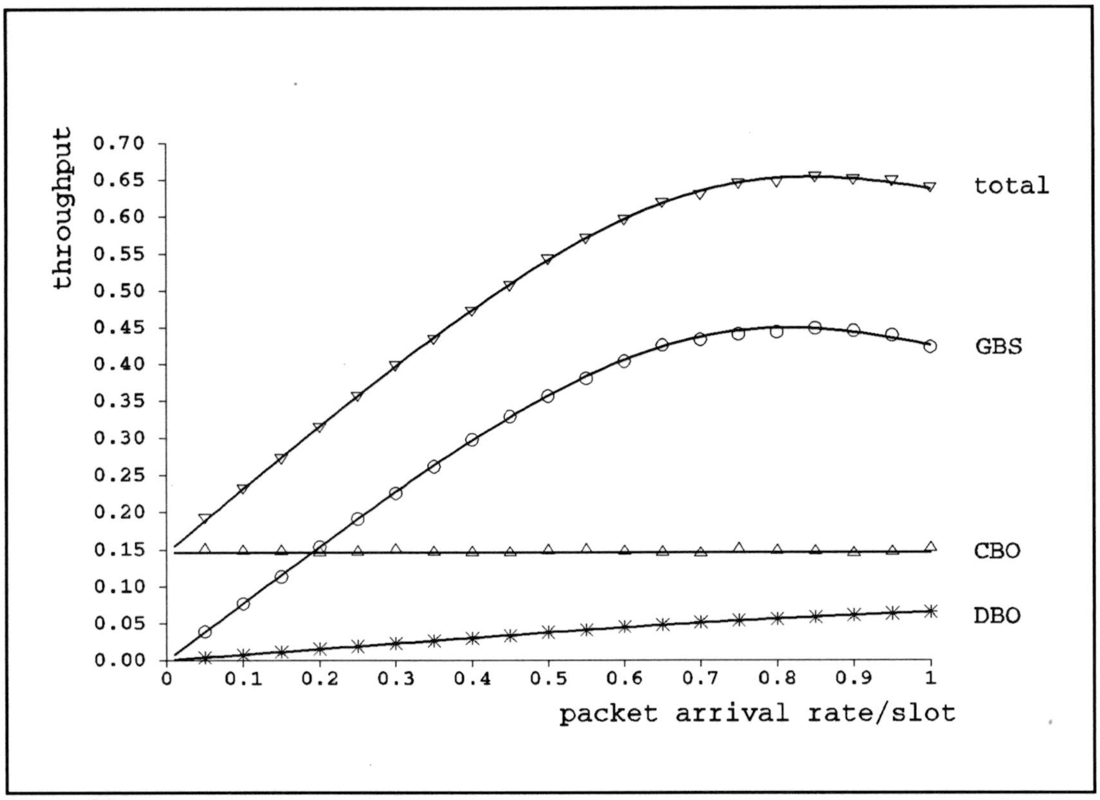

Fig. 28: CBO,DBO, GBS and total throughput vs. packet arrival rate/slot, for: nrDBO=20; **inb_outb=0.1**; pd=0.1; pg=0.5; cbothr=0.15.

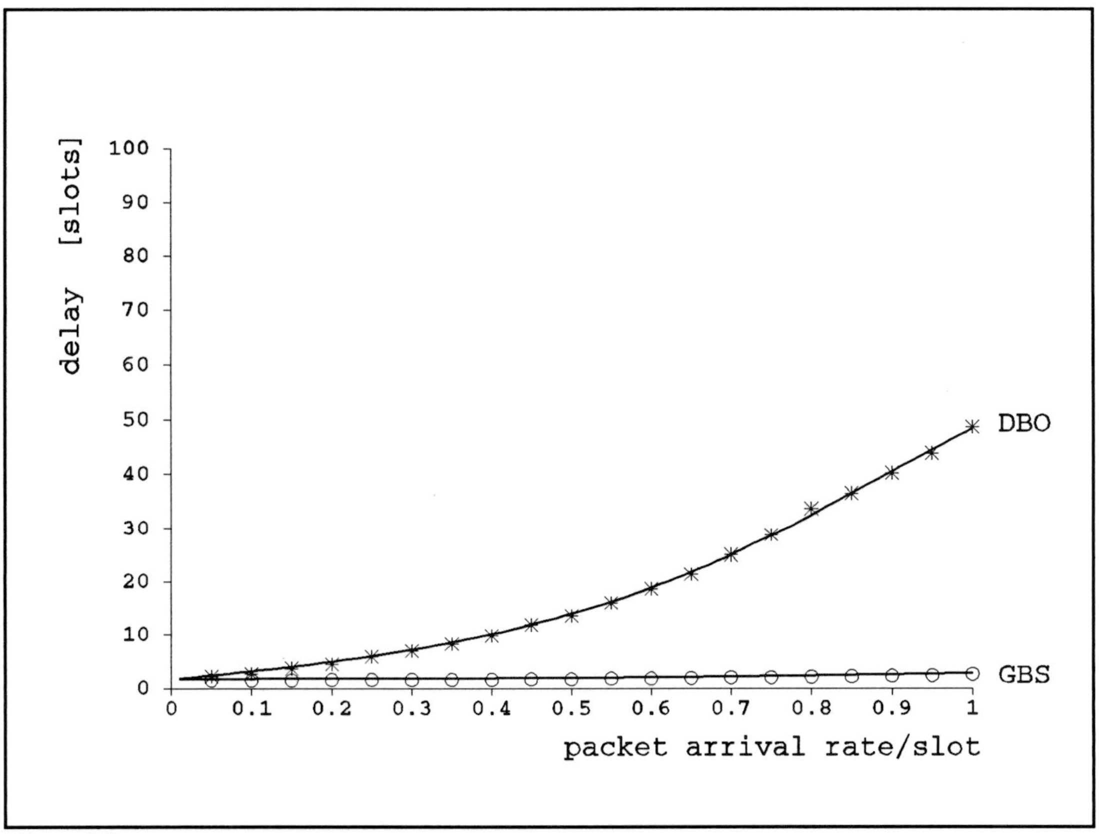

Fig. 29: DBO and GBS packet delay vs. packet arrival rate/slot, for: nrDBO=20; **inb_outb=0.1**; pd=0.1; pg=0.5; cbothr=0.15.

Figure 30 - 35 depict the results of a system where the number of DBO terminals in the group changes.

It can be concluded from these plots that the CRMA protocol can deliver a stable channel, and does not suffer from bistable behaviour as described in [17] and [18]. This is however only valid with small cell sizes, with a limited number of DBO users.

The system of figure 30 and 31 has only one DBO terminal. But because of the low retransmission probability "$p_d = 0.1$" a newly arrived packet, is more likely to find the terminal backlogged, because it is waiting for a transmission attempt. In this case a lot of "free" slots are not accessed by the terminal or the GBS. This can be concluded because at higher transmission rate the packet delays hardly increase.

Figure 32 and 33 give a system with 8 DBO terminals in the group. In this case the number of collisions at higher traffic rates slightly increases. The terminals will therefore more frequently be in the backlogged mode witch results in a higher packet delay.

A system with about 20 DBO terminals, still has a good throughput and delay performance, with the chosen retransmission probabilities, as can be seen in the figures 34 and 35. At higher traffic rates the throughput will decrease a little, but the system will not get saturated, and therefore the packet delays are still low.

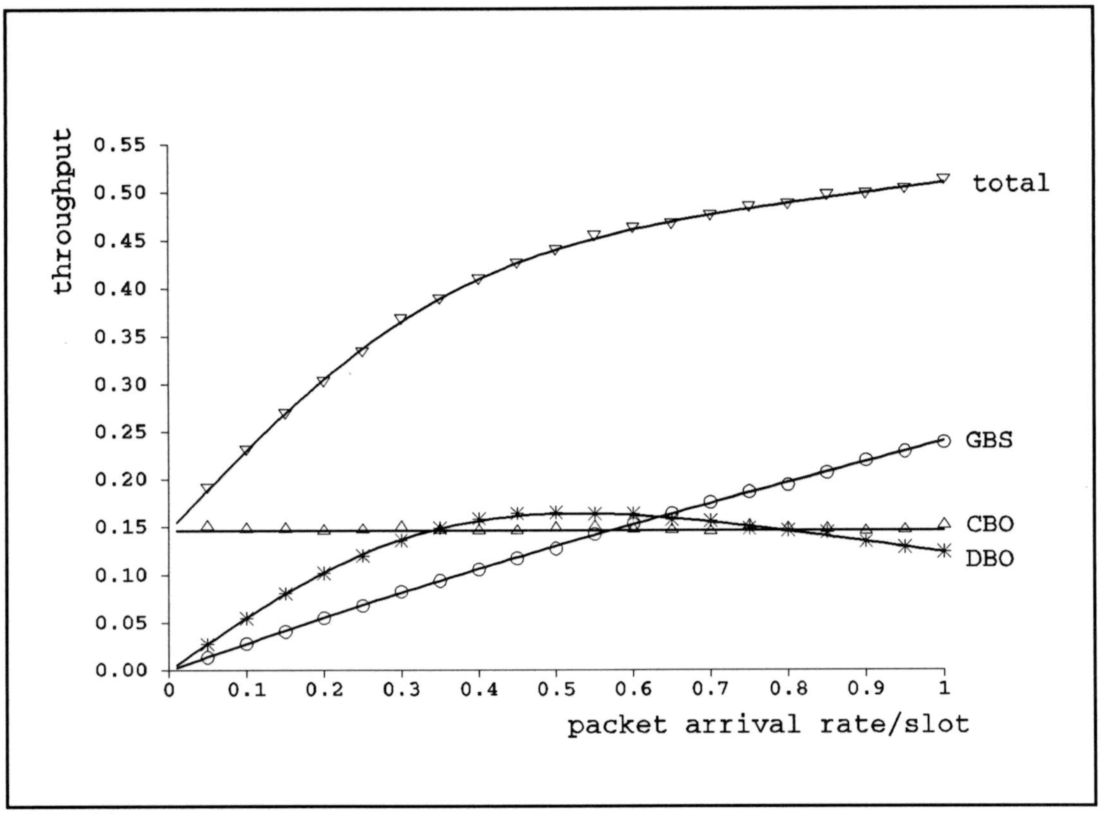

Fig. 30: CBO,DBO, GBS and total throughput vs. packet arrival rate/slot, for: **nrDBO=1**; inb_outb=2; pd=0.1; pg=0.5; cbothr=0.15.

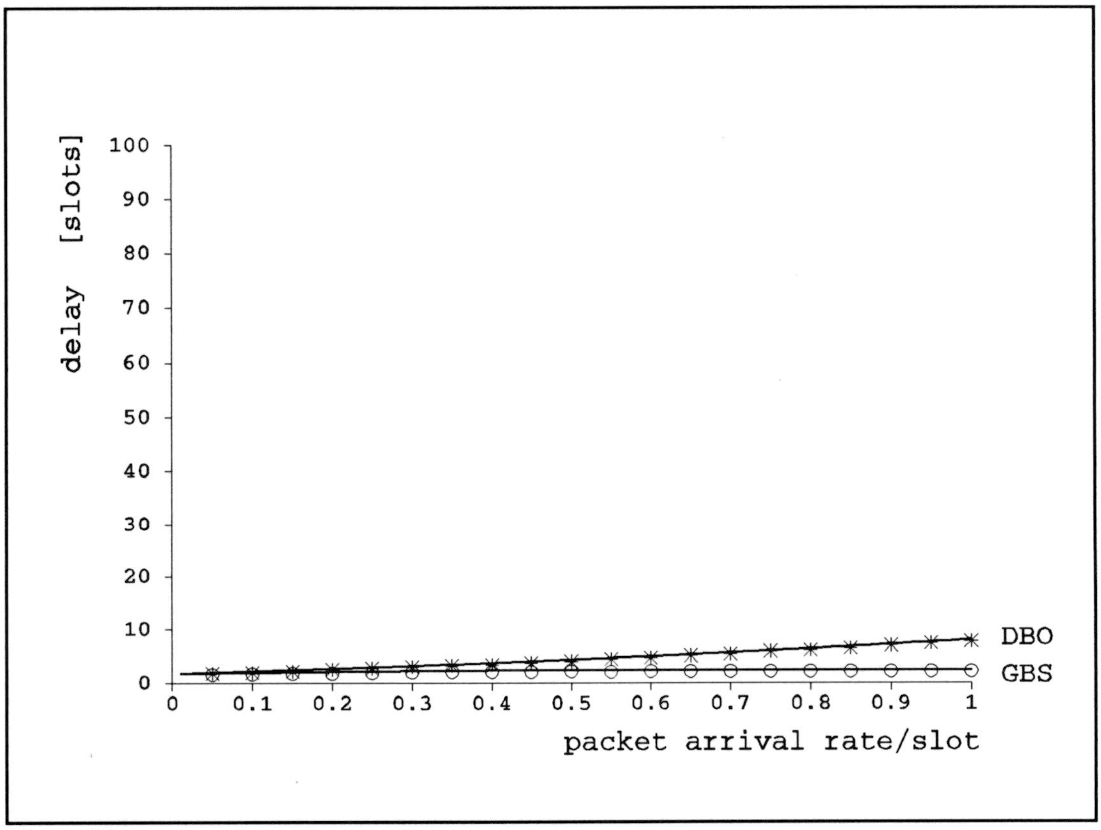

Fig. 31: DBO and GBS packet delay vs. packet arrival rate/slot, for: **nrDBO=1**; inb_outb=2; pd=0.1; pg=0.5; cbothr=0.15.

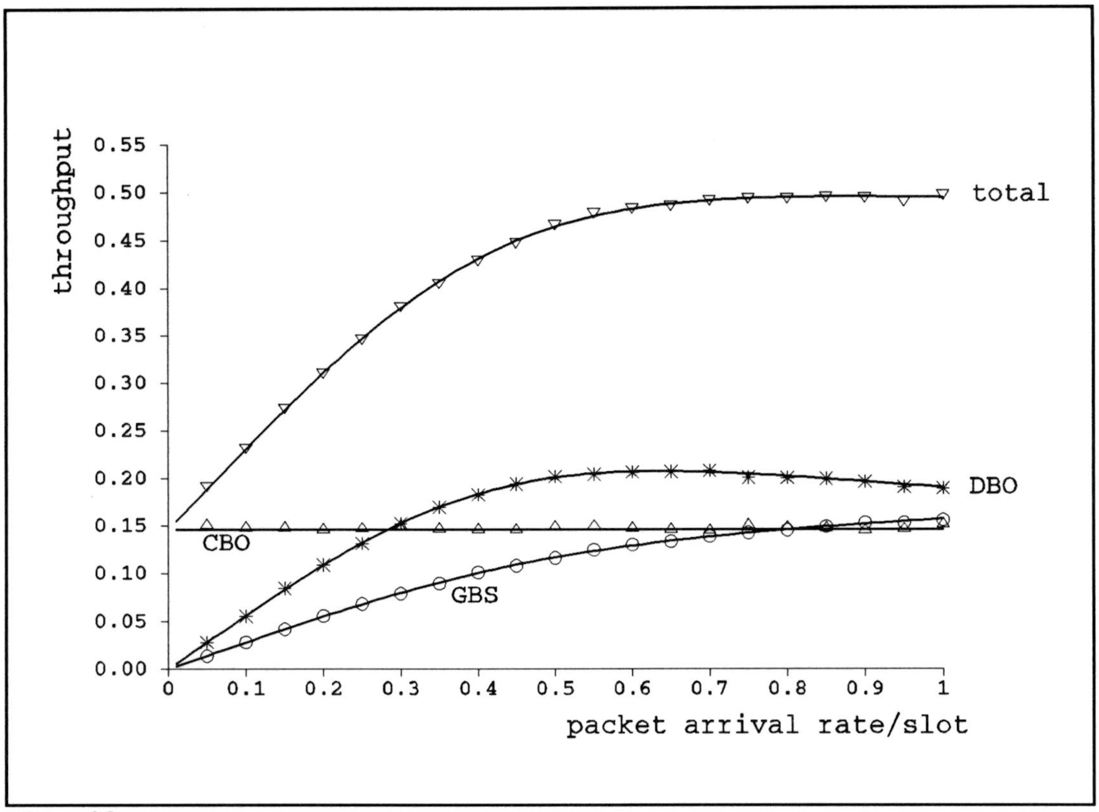

Fig. 32: CBO,DBO, GBS and total throughput vs. packet arrival rate/slot, for: **nrDBO=8**; inb_outb=2; pd=0.1; pg=0.5; cbothr=0.15.

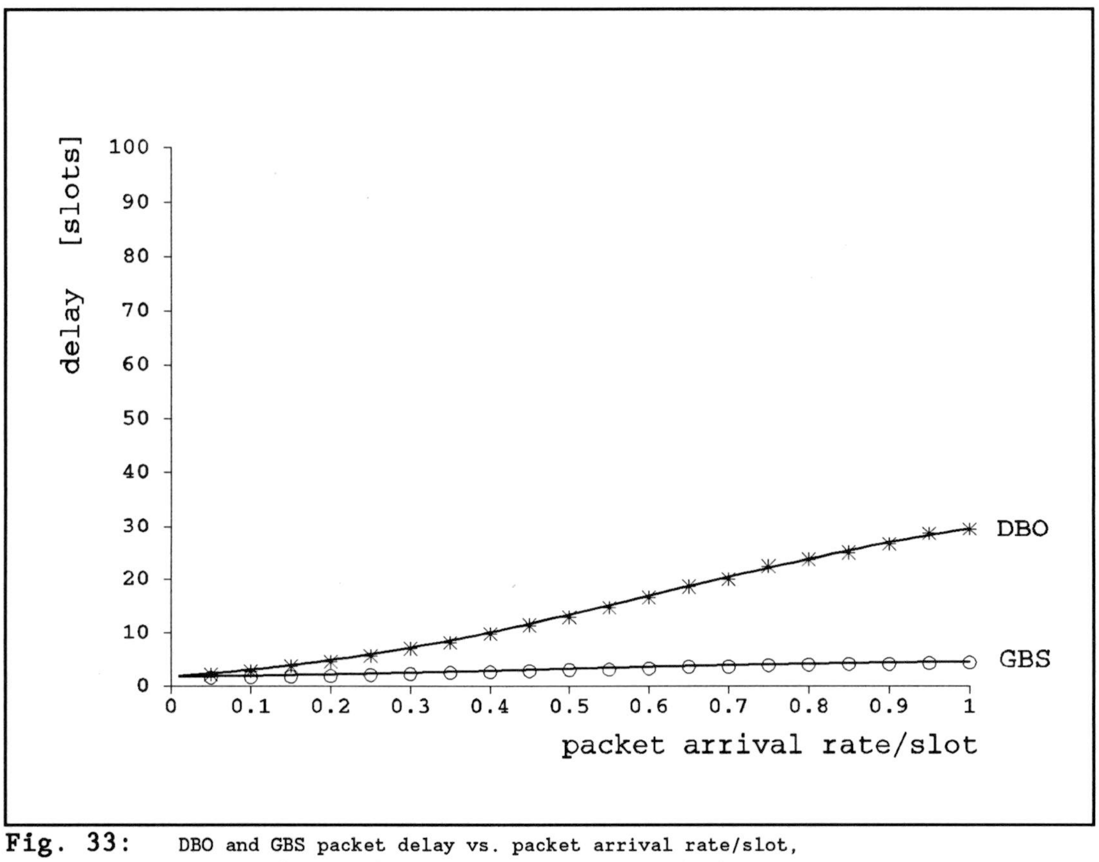

Fig. 33: DBO and GBS packet delay vs. packet arrival rate/slot, for: **nr.dbo=8**; inb_outb=2; pd=0.1; pg=0.5; cbothr=0.15.

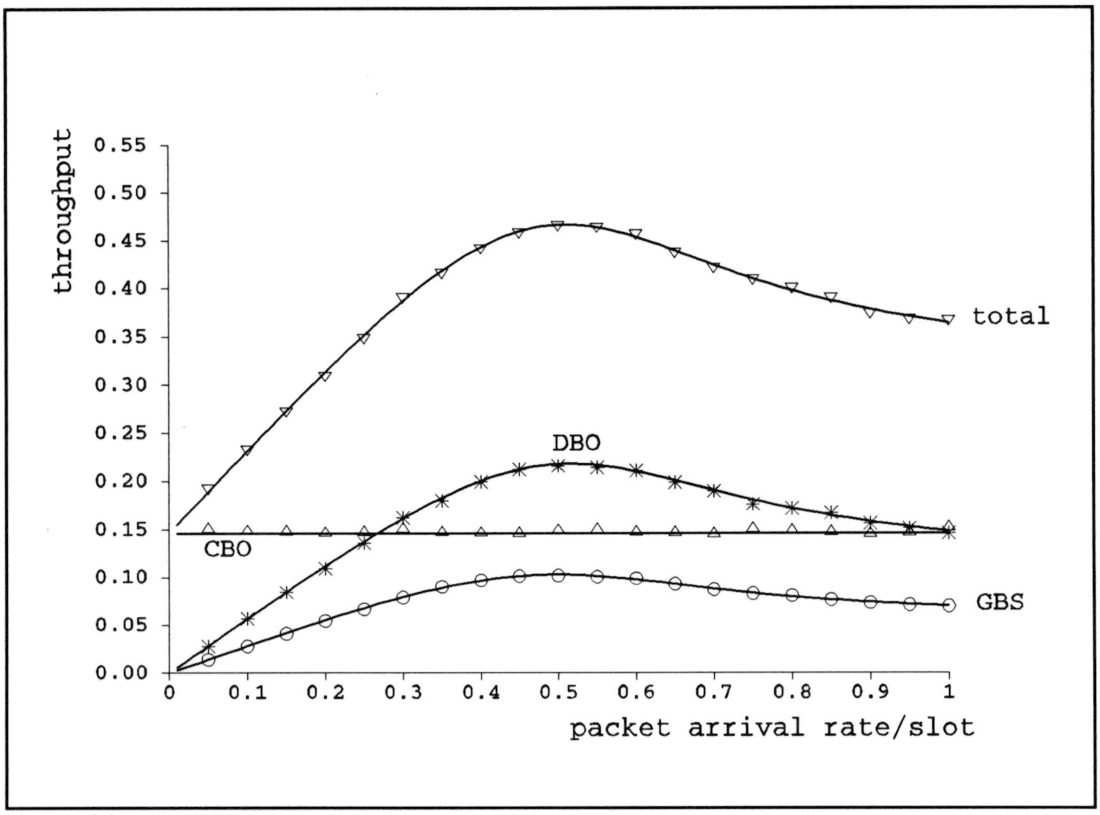

Fig. 34: CBO,DBO, GBS and total throughput vs. packet arrival rate/slot, for: **nr.dbo=20**; inb_outb=2; pd=0.1; pg=0.5; cbothr=0.15.

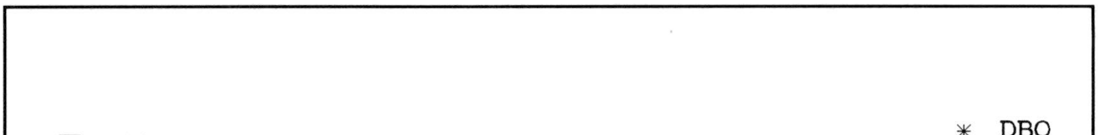

Fig. 35: DBO and GBS packet delay vs. packet arrival rate/slot, for: **nrDBO=20**; inb_outb=2; pd=0.1; pg=0.5; cbothr=0.15.

Figure 36 - 41 show the influence of variation of the retransmission probability "p_g" by the GBS on the system performance.

It can be concluded from this variation that the system performance is improved, by choosing a proper value for p_g.

If we look at the figures 36 and 37, it can be seen that a high value of p_g, results in good performance for the GBS. The GBS throughput equals over a wide range of the packet arrival rate, about 10 % of the system capacity. The delay of packets transmitted by the GBS is also very low over the complete range, with a maximum of 9 slots.
The good performance for the GBS however results in a degraded performance for the DBO terminals, which suffer more packet collisions, and therefore much higher transmission delays when the packet arrival rate increases.
Notice that the scale of figure 37 ranges up to 250 slots, while the scales of the figures 39 and 41 both range up to 100 slots.

When the retransmission probability of the GBS decreases to 0.5 as shown in figure 38 and 39, the systems has a more fair behaviour for both the GBS and the DBO terminals. Both suffer a little decrease in throughput with an acceptable increase of packet delay at higher loads.

If the value of p_g decreases to 0.1, as shown in the figures 40 and 41, it again results in an unfair system. In this case the DBO terminals experience a good performance in spite of the GBS.
Therefore the GBS throughput at maximum reaches about 6% of the link capacity. The DBO throughput however reaches to about 26% of the link capacity, which is considerably more than the maximum value of 20% with the higher values of p_g.

Because the retransmission probability in the last system by the GBS is equal to that of the DBO terminals, the average packet delay is approximately equal in both directions. However packets transmitted by the DBO terminals have to compete with 19 little streams from the other DBO terminals and one big stream from the GBS. Packets transmitted by the GBS only has to compete with 20 small traffic streams from the DBO terminals. Therefore the DBO delay is a little higher than the GBS delay.

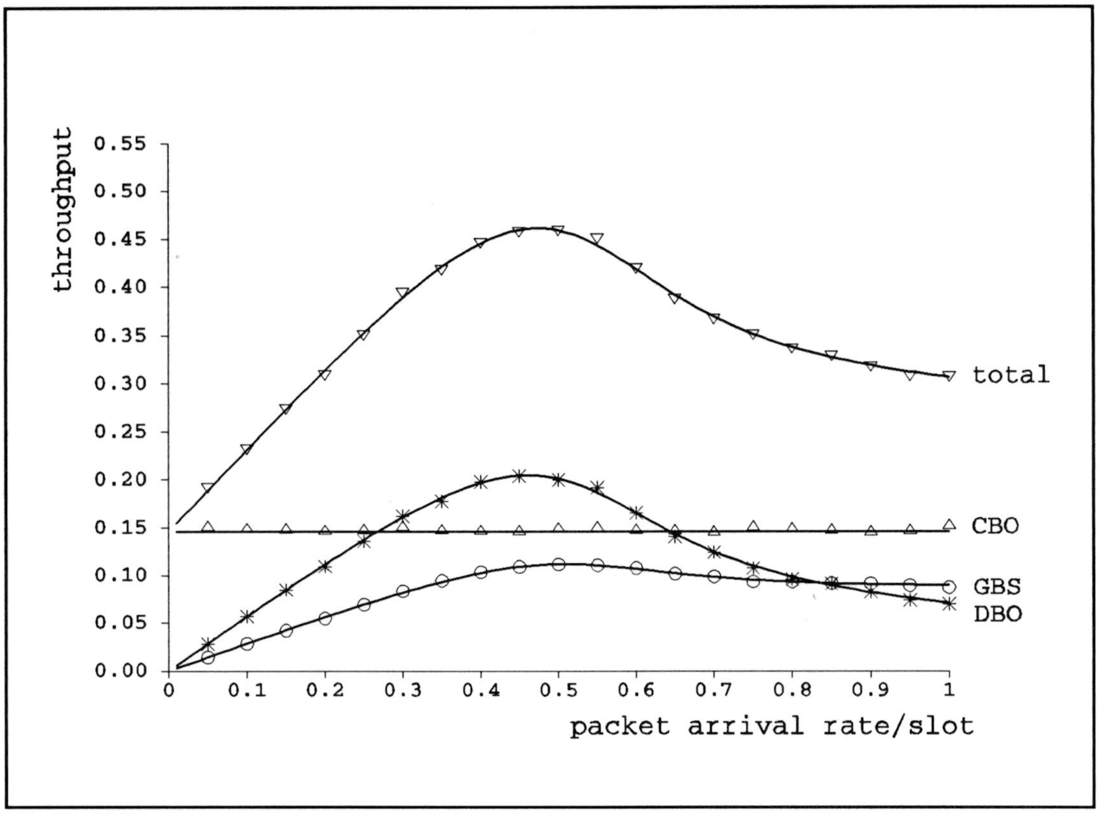

Fig. 36: CBO,DBO, GBS and total throughput vs. packet arrival rate/slot, for: nrDBO=20; inb_outb=2; pd=0.1; **pg=0.9**; cbothr=0.15.

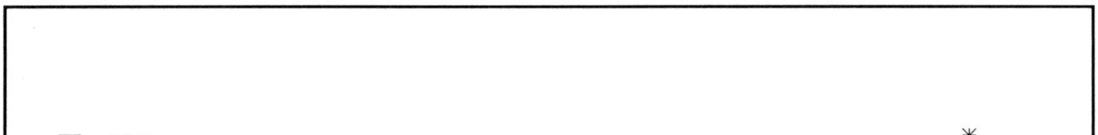

Fig. 37: DBO and GBS packet delay vs. packet arrival rate/slot, for: nrDBO=20; inb_outb=2; pd=0.1; **pg=0.9**; cbothr=0.15.

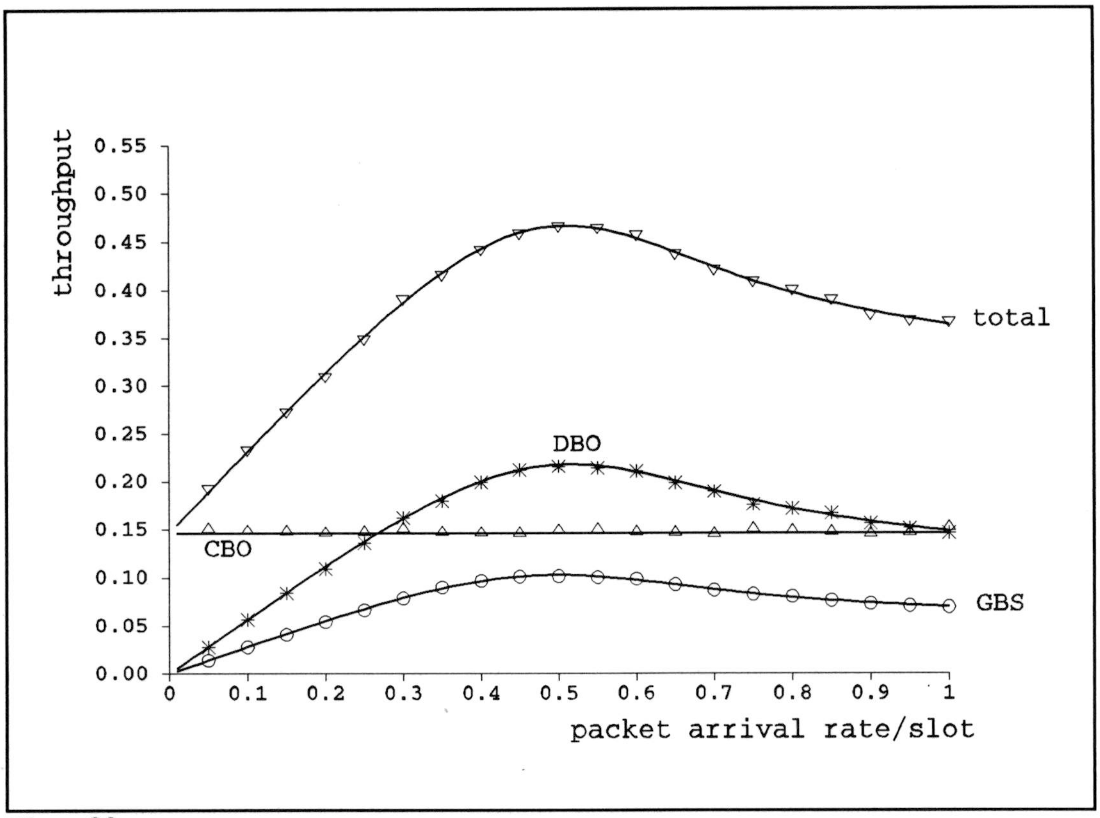

Fig. 38: CBO,DBO, GBS and total throughput vs. packet arrival rate/slot, for: nrDBO=20; inb_outb=2; pd=0.1; **pg=0.5**; cbothr=0.15.

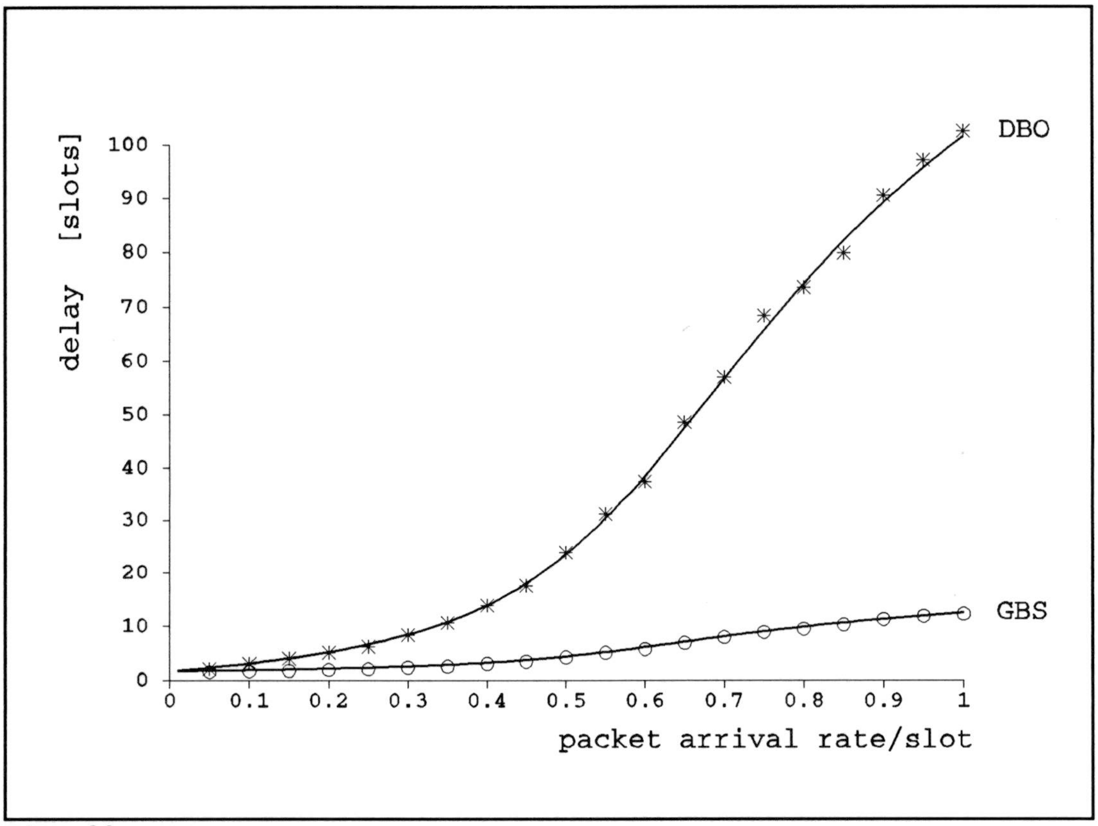

Fig. 39: DBO and GBS packet delay vs. packet arrival rate/slot, for: nrDBO=20; inb_outb=2; pd=0.1; **pg=0.5**; cbothr=0.15.

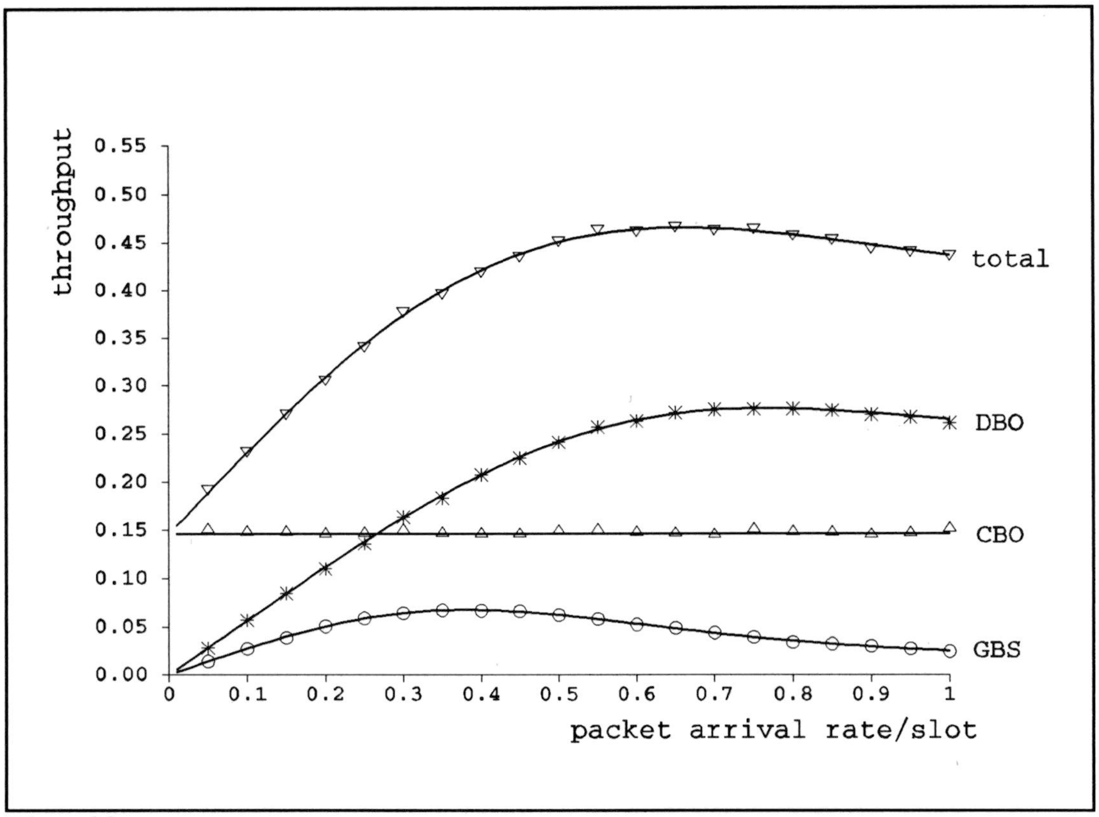

Fig. 40: CBO,DBO, GBS and total throughput vs. packet arrival rate/slot, for: nrDBO=20; inb_outb=2; pd=0.1; **pg=0.1**; cbothr=0.15.

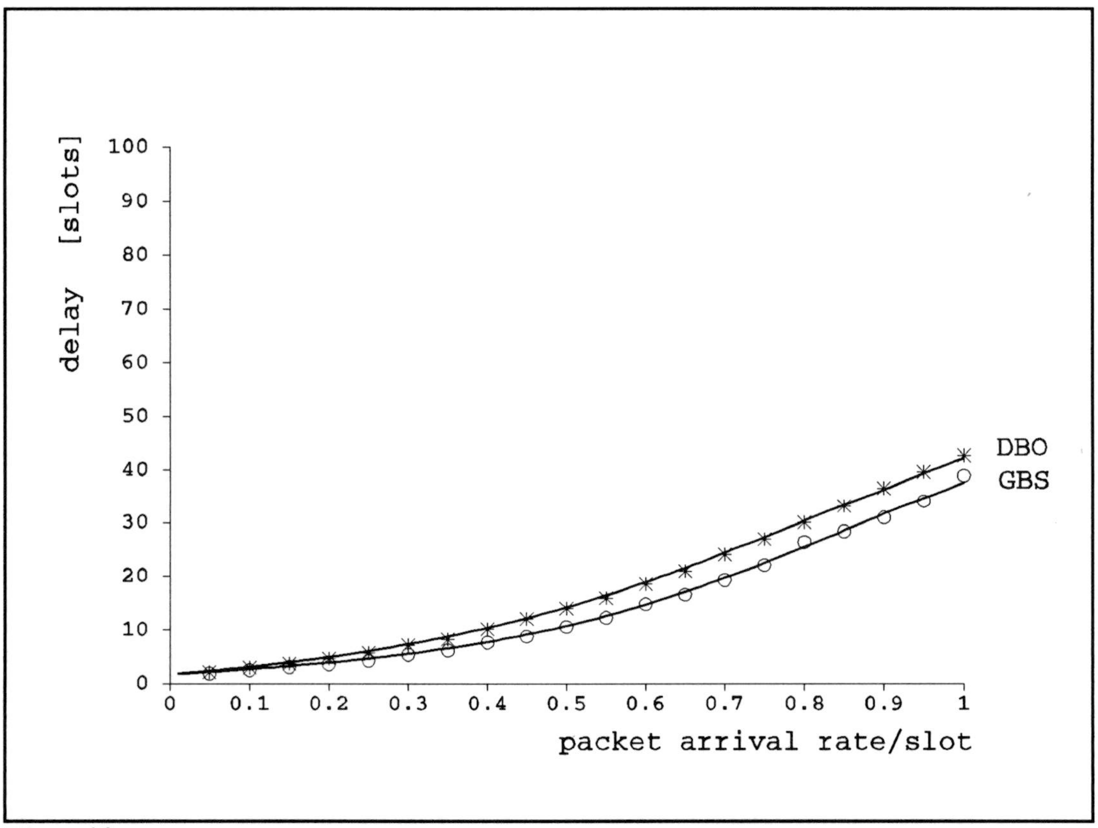

Fig. 41: DBO and GBS packet delay vs. packet arrival rate/slot, for: nrDBO=20; inb_outb=2; pd=0.1; **pg=0.1**; cbothr=0.15.

The figures 42 - 47 give an indication of the system performance under variation of the retransmission probability by one of the DBO terminals "p_d". These figures can also be compared with for example the figures 38 and 39 which has a p_d value of "0.1" and the other values equal to that of the systems in figure 42 - 47.

These graphs show that when proper values are chosen for the retransmission probability for a DBO terminal "p_d", the system performance can be optimised.

The system of figures 42 and 43 has a relative high value of p_d, which results in a link which can get saturated, and therefore has the undesirable bistable behaviour [17], [18]. In comparison with all other plots the experienced delays are very high for both the DBO terminals as the GBS.

If p_d has a value of 0.05 as shown in the figures 44 and 45, the system has a very good performance for both the DBO as the GBS traffic. The DBO throughput reaches over a wide range at a high level of 20% of the link capacity. The GBS throughput can easily reach to about 15%, which is considerably more than the value of 10% in figure 38. This without the degradation of the DBO performance. A system with $p_d = 0.05$ also leads to acceptable packet delays as can be concluded from figure 45.

If an even lower value of $p_d = 0.02$ is chosen the system performance, for the DBO terminals will decrease, in favour of the performance of the GBS. See the figures 46 and 47. The DBO throughput in this case has a maximum value of about 17 %, with a still acceptable delay. The packets from the GBS suffer very little collisions in this case, and therefore the packet delay is very low. The GBS throughput is expected to reach a higher value than that of 20% at higher packet arrival rates.

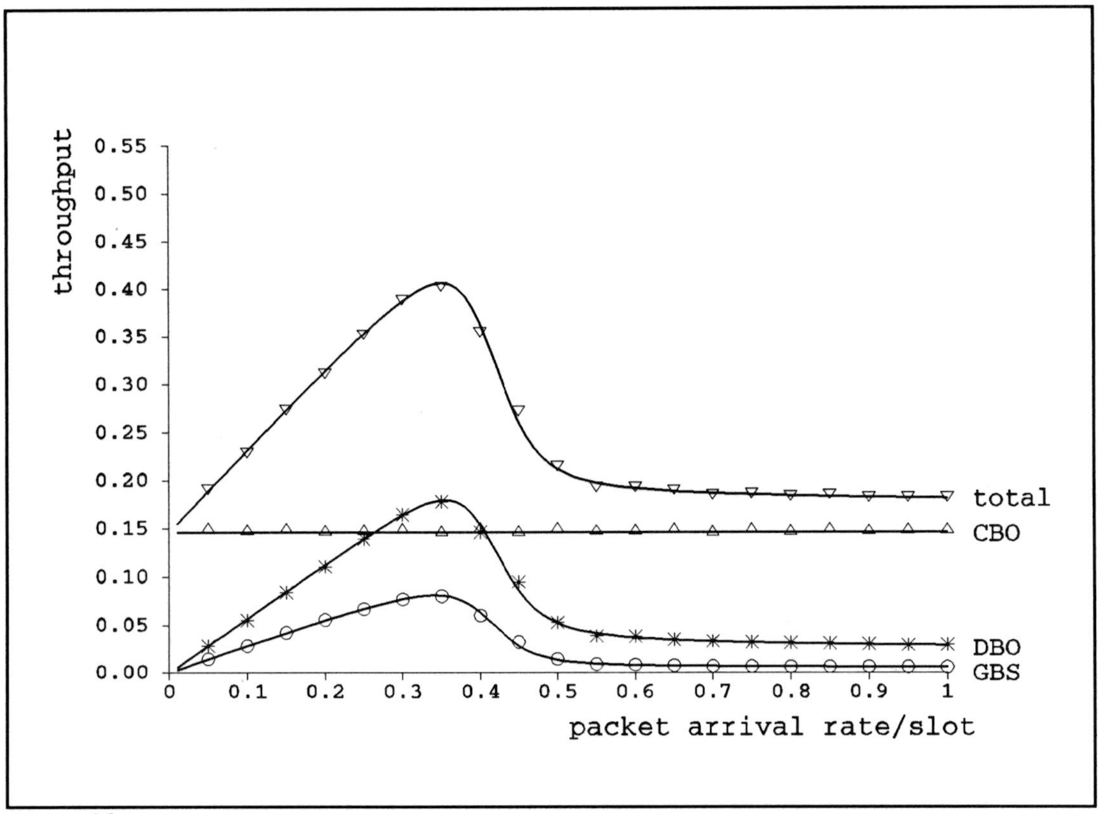

Fig. 42: CBO,DBO, GBS and total throughput vs. packet arrival rate/slot, for: nrDBO=20; inb_outb=2; **pd=0.2**; pg=0.5; cbothr=0.15.

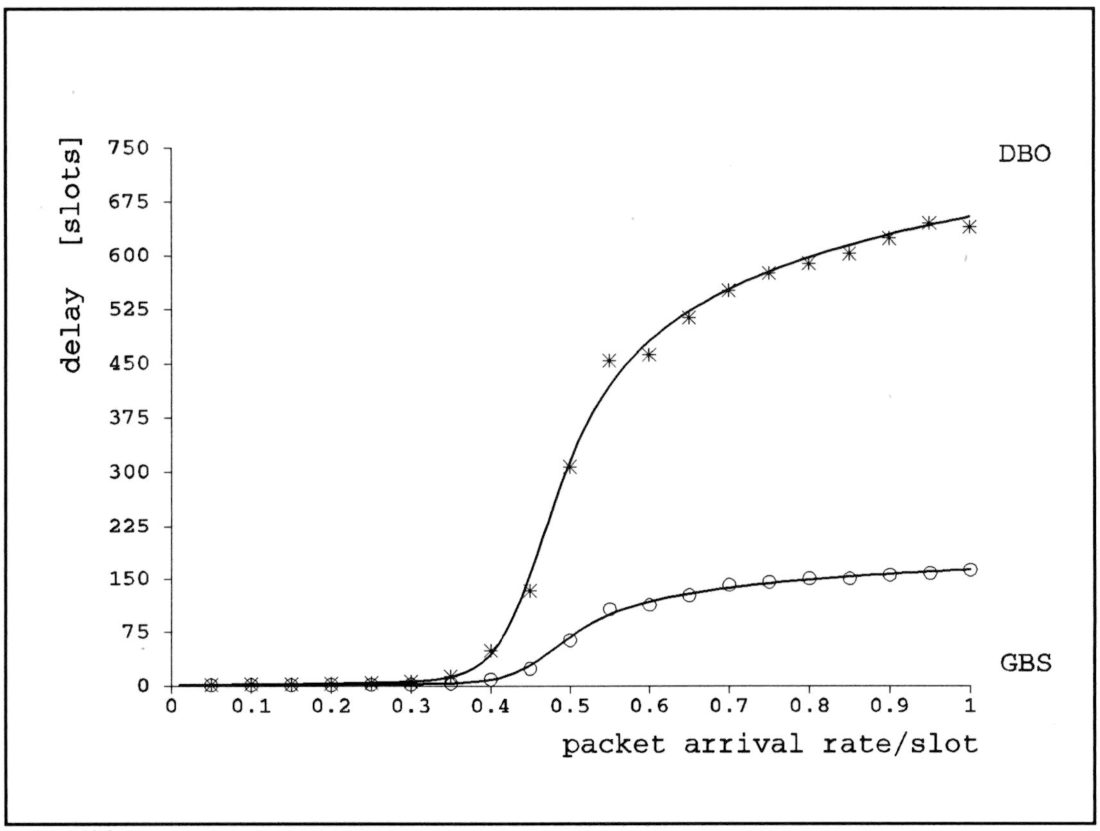

Fig. 43: DBO and GBS packet delay vs. packet arrival rate/slot, for: nrDBO=20; inb_outb=2; **pd=0.2**; pg=0.5; cbothr=0.15.

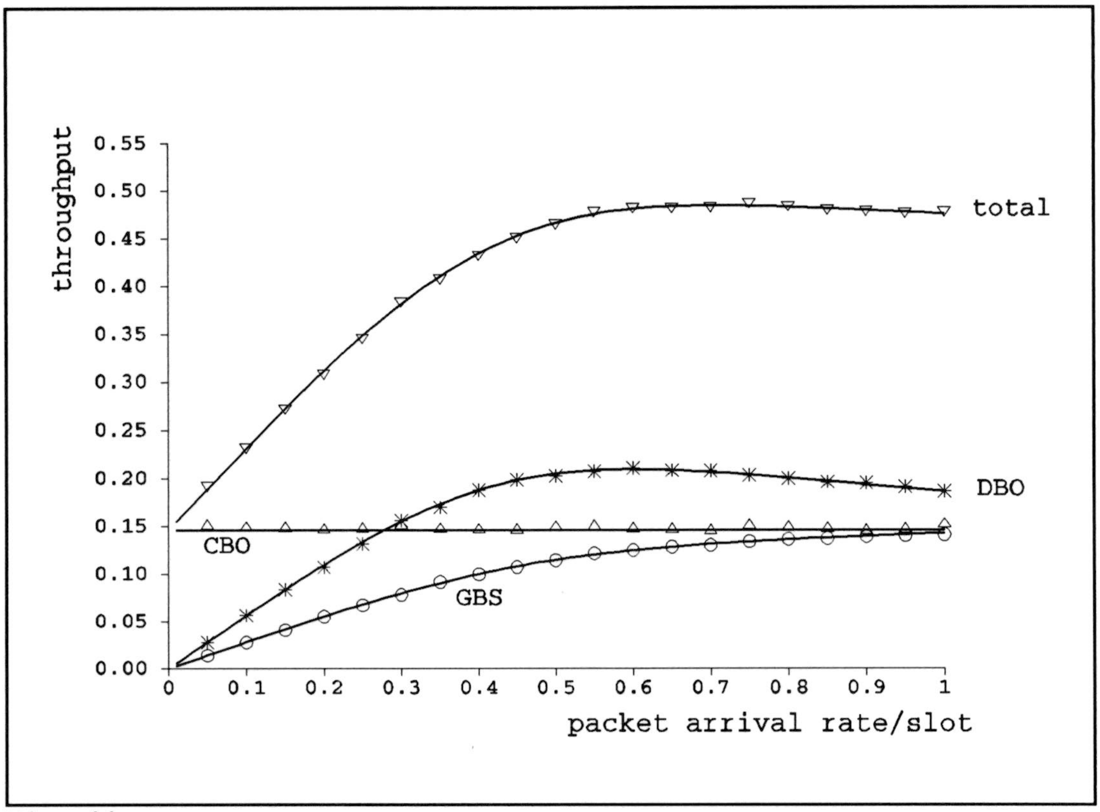

Fig. 44: CBO,DBO, GBS and total throughput vs. packet arrival rate/slot, for: nrDBO=20; inb_outb=2; **pd=0.05**; pg=0.5; cbothr=0.15.

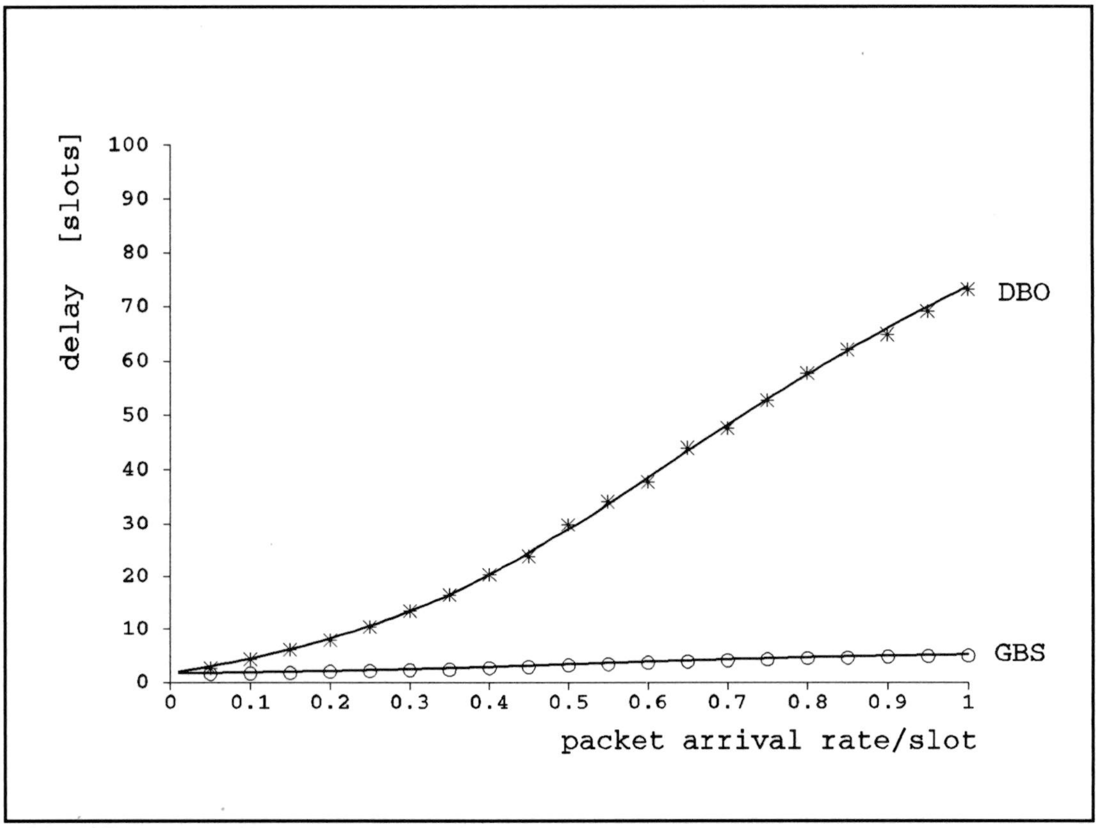

Fig. 45: DBO and GBS packet delay vs. packet arrival rate/slot, for: nrDBO=20; inb_outb=2; **pd=0.05**; pg=0.5; cbothr=0.15.

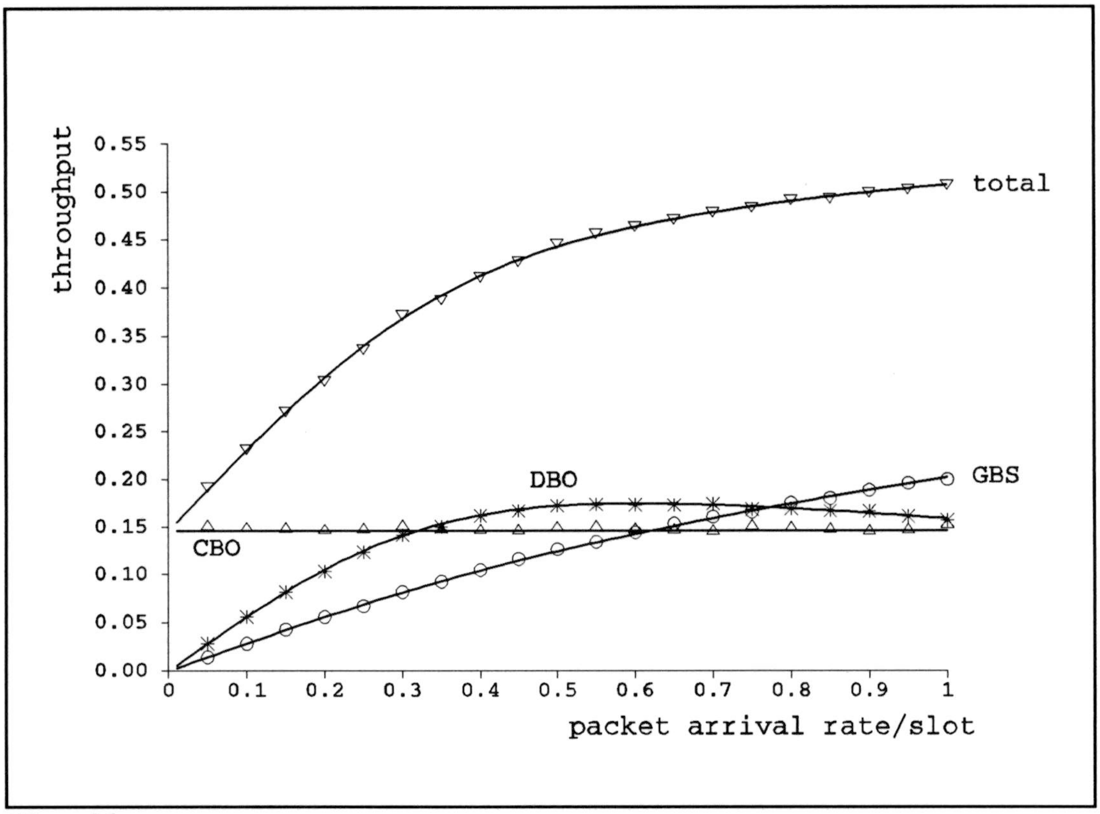

Fig. 46: CBO,DBO, GBS and total throughput vs. packet arrival rate/slot, for: nrDBO=20; inb_outb=2; **pd=0.02**; pg=0.5; cbothr=0.15.

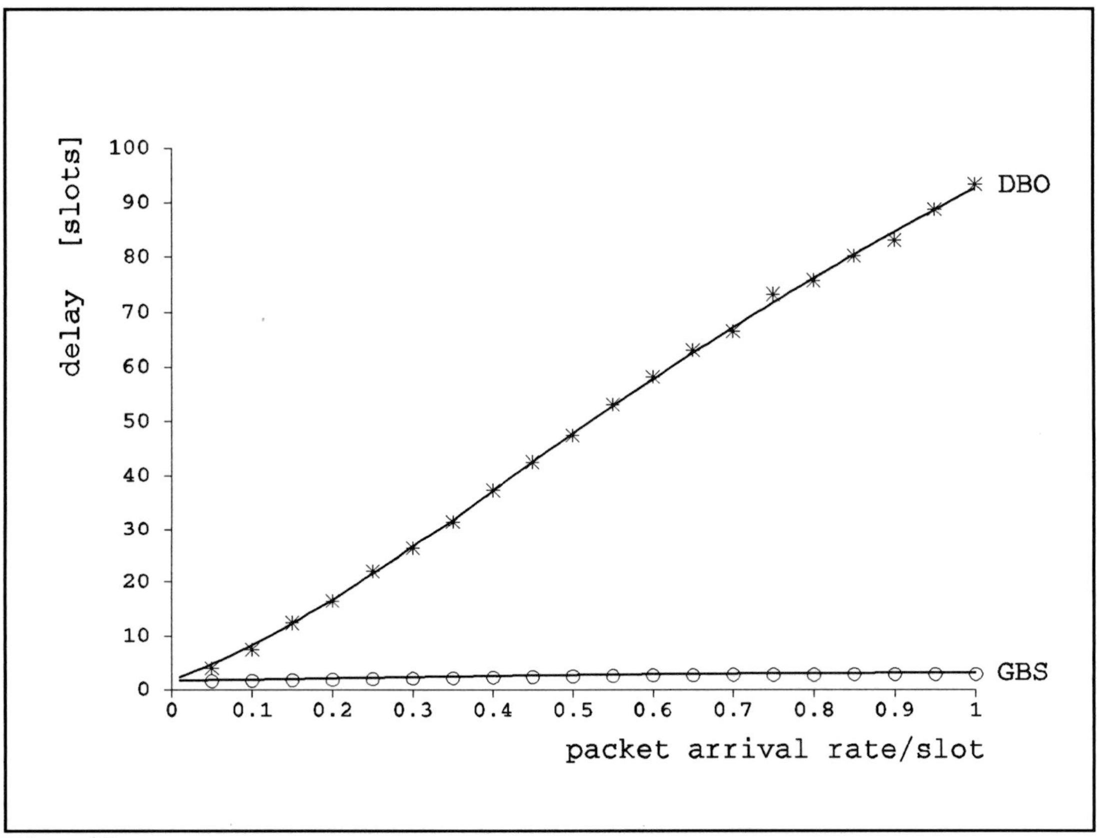

Fig. 47: DBO and GBS packet delay vs. packet arrival rate/slot, for: nrDBO=20; inb_outb=2; **pd=0.02**; pg=0.5; cbothr=0.15.

6 EVALUATION OF CRMA AND COMPARISON WITH OTHER VOICE/DATA PROTOCOLS.

Several protocols can be found in literature, which optimise the network performance for traffic types, which require a divergent quality of service. Some of them also use the bandwidth left unused by speech sources in silent periods.
In this chapter first a discussion of the CRMA features are given. Thereafter a short description of four protocols, presented in literature follows. After the description of each protocol a comparison with the CRMA protocol is made.
Because the performance results of these protocols are presented in a incomparable way, it is difficult to give a quantitative comparison. Therefore this evaluation will concentrate on the qualitative aspects.

6.1 Evaluation of the CRMA protocol.

The characteristics of the CRMA protocol are listed in this section. Some follow directly from the protocol description in chapter 3, whereas others are demonstrated analytically and by simulation in chapter 5.

i) The CRMA protocol guarantees the allocated bandwidth for CBO traffic types.

ii) The link capacity left unused by the CBO traffic is available for contention by the DBO sources. These access the remaining capacity according to a contention type access mechanism.

iii) The maximum channel utilisation for the CRMA protocol is dependant on the type of traffic streams, the ratio between the inbound and outbound arrival rates and the number of DBO terminals in the group.

iv) If for the CBO traffic only speech is considered, which has a talkspurt fraction of "$p_{talk} = 0,426$", the throughput for this type can vary between 0 and 0,426.

v) The throughput for the DBO traffic, uses the remaining capacity, after the CBO part has been subtracted from the total link capacity. The maximum utilisation of this part of the capacity can vary between 37% with mostly traffic from the DBO terminals, up to 60 % when there is almost only outbound traffic from the GBS.

v) For the DBO packets the CRMA protocol achieves very low packet delays of not more than about 150 slot periods, if the values of p_d and p_g are not chosen too extreme.
If the same transmission parameters are chosen as with the comparable PRMA protocol, as described in [6], this maximum packet delay equals about 120 msec.
In [6] a transmission rate of 720 kbit/s is assumed and the number of bits per packet 576, which results in a slot duration of 0,8 msec.

vii) The delay of CBO packets is very low and never exceeds the duration of one frame period. In [6] this frame period lasts 16 msec.

viii) The link utilisation for the DBO traffic can be optimised, by choosing proper values for the retransmission probabilities for the DBO terminals and the GBS, p_d and p_g respectively .

ix) CRMA is a very simple protocol, in which very little CONTROL information has to be exchanged. Therefore the performance of the protocol is little sensitive to CONTROL packets which get lost. The only necessary CONTROL information, are the clock synchronisation and the indication to CBO terminals, which slots have to be used.

x) The number of CBO users, which simultaneously have a connection with another CBO terminal is restricted by the number of slots in a frame. Because the cell size in a cellular system has to be as small as possible for a high spectrum efficiency, this maximum allowed number of connections will not be a bottleneck.

xi) The half duplex protocol yields less average packet delays and allow simpler receivers than full duplex communications, where the bandwidth is split equally among inbound and outbound traffic. When the difference between the size of these traffic stream is large, for the full duplex communication at least one link has a very poor utilisation. On the other hand for CRMA, the small stream has a minor impact on the total throughput, and therefore hardly effects the link utilisation.

xii) All contention type protocols have in common that they are inherently unstable. Several ways have been proposed to stabilise these type of protocols. [19] .. [21]

This instability may also occur with the CRMA protocol, for the fraction of the DBO bandwidth, making a stabilisation scheme necessary. However as can be concluded from the performance results, bistable behaviour does not occur when the number of DBO users in a group is not very large. Because of the small cell size, a group does not consist of a large amount of DBO users.

xiii) The transmitting station can determine in a very short time if the transmission has been successful, because the acknowledgement directly follows, after the last data bits has been received by the receiving station.

6.2 The PRMA protocol.

Packet Reservation Multiple Access (PRMA) is a slotted contention protocol, which allows a mixture of voice packets and packets from data sources over short range full duplex radio links.
In [6],[14] and [22] a detailed description of the PRMA protocol is given. In [23] the packet dropping probability is presented for the PRMA protocol. More PRMA performance results can be found in [15] and [24].

With PRMA, slots are dynamically reserved for active voice terminals in each frame. The CBO user has to contend for reservation of the time slot by first transmitting a packet successfully at the beginning of every talkspurt. On successful transmission of a CBO packet the GBS grants reservation of the time slot in future frames to that CBO source. After the source has finished transmitting all its packets during a talkspurt, it leaves a slot blank which indicates that from the next frame, this slot is free for contention.

In case of DBO packets there is no reservation facility. Terminals have to contend for successful transmission of their packets in every frame. DBO terminals can only contend for time slots which are not reserved. The contention is done using the slotted ALOHA protocol. [25],[26].

During contention, if a packet stays in the terminal buffer for a very long time the oldest packet is discarded, and new packets are admitted in the buffer. DBO buffers can be longer than speech buffers.

With PRMA, most packet losses for speech traffic, occur at the beginning of talkspurts. This results in a high correlation between the DBO packet arrival rate and the loss probability for speech traffic.

At the end of every slot an acknowledgement is given by the receiving station for both the CBO and the DBO traffic.

Data, acknowledgements and CONTROL data to the CBO and DBO terminals, are sent in the outbound channel of the full duplex link by the GBS.

When a slot is reserved by a CBO source for future use, the GBS broadcasts a signal "reserved" to all the group users for this slot, otherwise a signal "available" is sent out for this slot.

The advantages of CRMA over this PRMA protocol are.

- CBO packet loss will be zero with CRMA, because there is no front end clipping at the beginning of every talkspurt.
- Lower CBO delay because there is no buffering.
- Loss probability of CBO packets, which only occurs in case of channel impairments, is not correlated with the arrival rate of DBO packets.
- No destination header has to be part of the CBO packets, because fixed slots are used for every connection.
- PRMA is full duplex, which has several disadvantages compared to the half duplex channel of CRMA, as mentioned in section 7.1.(xi).
- No "reserve" and "available" signals have to be broadcast. Frame reservation registers are not necessary in the CBO and DBO terminals.

Disadvantages of the CRMA protocol in comparison with PRMA are:

- To sense the channel at the beginning of the slot period by a DBO station, a small fraction of the link capacity is left unused. With the transmission parameters as mentioned in 6.1.(v) and a worst case propagation delay of 1 μsec, the link is left unused, because of sensing the channel, for a percentage less than 0,25 %.
- With PRMA higher number of simultaneously speech conversations can be serviced. However with small cell sizes, the restriction of the maximum number of CBO connections in CRMA will not be a bottleneck, as already mentioned in 6.1.(x),

6.3 The Reservation Multiple Access Protocol.

The Reservation Multiple Access Protocol described in [27] is a modified version of the PRMA protocol. It has a guaranteed reservation capacity, which results in less front end clipping.
With this protocol the reservation of a slot in a frame for the transmission of a speech packet is done different from PRMA.

In the frame structure one or more slots are specifically assigned as a permanent reservation channel. This reservation channel is divided into minislots. The slotted ALOHA protocol is used in these minislots, to transmit a "reservation" signal by one of the speech terminals. After successfully transmitting a reservation signal, one of the information slots in the frame structure is assigned to the terminal by the GBS, for the transmission of a voice packet.
The assigned information slot is reserved for the terminal until the end of the talkspurt period. At the beginning of every talkspurt, a new reservation has to be done.

This Reservation Multiple Access Protocol behaves under light load conditions much like the PRMA protocol.
At high load conditions, with PRMA the probability of finding a free slot for a reservation decreases, and more packets at the beginning of a talkspurt are lost because the maximum delay is exceeded. At the other hand for the Reservation Multiple Access protocol, there is always a minimum capacity left for reservations, resulting in a lower probability of the front end clipping.

The Reservation Multiple Access protocol has most disadvantages in comparison with CRMA in common with the PRMA protocol mentioned in the former section. An important drawback, a high level of front end clipping, however is much reduced by the introduction of the reservation channel.

The reservation channel is introduced at the cost of a small part of the link utilisation.

6.4 A polling protocol with a movable boundary.

In [28] a full duplex protocol for the integration of voice and data packets in a movable boundary TDMA system is described.
A frame is divided into two regions with a boundary between them. The first region is used for both voice and data traffic, where the voice traffic has priority. If not all slots in this region are occupied by the voice packets, the remaining slots are used by the data traffic. The second region is reserved for the data traffic only. The boundary between the voice and data moves in accordance with the active voice packets in each frame.

During a call setup the GBS assigns a sequential identification (ID) number to the CBO users. The CBO user with the lowest ID number is given permission to start the transmission. If there is no packet in the buffer, a signal is sent to notify the GBS. After completion of the first message, the GBS informs the user with the next sequential ID number to start the transmission. This process continues until the boundary is reached or the last voice number has arrived.

The transmission of the DBO packets starts immediately after the voice packets and stops after the end of the frame time. The data traffic is handled by conventional polling. Once a DBO terminal is polled and receives permission to transmit, it can use all the remaining slots until its buffer is emptied. Then the GBS polls another DBO terminal and the same process is repeated.

This protocol has the disadvantages going along with polling as mentioned in [25] and [26]. With polling a lot of overhead is introduced. Therefore with a lot of terminals in a group the polling messages will demand a lot of the system capacity, and the response times for DBO data can significantly increase

Just like with the CRMA protocol a guaranteed bandwidth is achieved for CBO traffic.

6.5 The MCMA protocol.

The Minipacket Competition Multiple Access (MCMA) protocol presented in [29], can be compared with the above mentioned polling protocol.
It is a half duplex protocol in which the polling overhead is decreased. This is done by transmitting only one polling message for all DBO users, which thereafter all have to contend for the transmission of a data packet.
CBO users are proposed to be serviced in a similar way as the protocol of section 6.4.

If a DBO terminal in the group has a packet for transmission it waits for the polling signal by the GBS. Thereafter it competes for the channel by transmitting a minipacket. If this minipacket is correctly received by the GBS, the DBO terminal is authorised to transmit its full packet.
The protocol has been worked out for DBO data only, and the presented analysis shows protocol capacities in excess of 80 %.

Because no integrated traffic streams have been analyzed for MCMA it is difficult to compare this protocol with CRMA. However just like CRMA, the MCMA protocol seems to deliver a guaranteed CBO bandwidth combined with a high link utilisation.

7 CONCLUSIONS AND RECOMMENDATIONS.

In this report the new Circuit Reservation Multiple Access (CRMA) protocol for wireless office communication is presented.

Users with divergent service requirements and a group base station (GBS), all located in a small geographical area, transport their data over a common radio channel. Access to this half duplex radio channel is controlled by the CRMA protocol.

CRMA is a slotted protocol in which Continuous Bitstream Oriented (CBO) users, are assigned one or more slots for the duration of the connection. Users with a variable bandwidth demand are called Discontinuous Bitstream Oriented (DBO) users. They have to contend for slots not assigned to CBO users, or left unused by the CBO users in periods of silence.

The results of both an analytical and a simulation model, which have been built in this research match perfectly. Therefore it is assumed that the CRMA protocol model can be described by the analytical model, and the results of this model can be used for the evaluation of the CRMA protocol.

A cellular structure with cell sizes up to 300 m is considered. Each cell with a maximum of 20 CBO and 20 DBO users. With this population CRMA appears to deliver a stable channel, without the necessity of load control. The performance of the protocol can be optimised by adjusting the retransmission probabilities for the DBO terminals and the GBS.

For the CBO users the allocated bandwidth is guaranteed. The DBO users share the capacity left unused by the CBO users. With the chosen parameters the maximum utilisation of this remaining capacity can vary between 37% and 60%, and is independent of the height of the CBO throughput. The lower value is valid when the main traffic stream is towards the GBS, which is called inbound traffic, and produced by a number of bursty DBO terminals. The higher utilisation can be reached if there is mostly outbound traffic, produced by the GBS and destined for the group terminals.

Recommended items for further investigation related to the Circuit Reservation Multiple Access Protocol are:

i) Determination of an algorithm to find optimal values for the retransmission probabilities for the DBO terminals and the GBS. This has to be done to optimise the CRMA system performance for various traffic distributions.

ii) Investigation of the effect of different cell sizes on the stability and the spectrum efficiency of the CRMA protocol.

iii) Investigation of the characteristics and requirements of other services than speech and data with geometrically distributed inter arrival times, to find out if CRMA is also suited for those other traffic types.

iv) Analysis of the influence of the physical characteristics of the wireless office medium on the performance of the CRMA protocol.

v) Studying a complete office network consisting of several groups, each having its own CRMA controlled radio link, and the high speed backbone network.

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