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Virtual Circuit Reservation Multiple Access -protocol for mixed voice/data radio communications

by
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Abstract

This combination of papers describes two protocols proposed for wireless communications. The first paper gives the working and performance of a protocol for mixed voice/data radio communications with the name Virtual Circuit Reservation Multiple Access (VCRMA). The VCRMA protocol was designed for low gross speech rate of about 13 Kbps and high channel rate of about 2 Mbps. Those values of speech and channel rates are some of the objectives of the third generation of telecommunication systems. The VCRMA protocol can be used in all three types of cells (pico-, micro- and macro-) and its total system throughput is rather high. It is expected that the protocol will be one of the candidates for the protocols used in future Universal Mobile Telecommunication Systems (UMTS). The VCRMA protocol is especially suitable for environment with high demand in data communications such as office or industry. The ways to achieve the virtual concept of the protocol are discussed in the paper. A rule of thumb for design protocols which use the control mechanism of the VCRMA protocol is also given.

The second paper describes a protocol for wireless data communications with the name Modified Minipacket Competition Multiple Access (M-MCMA). The M-MCMA protocol is used for regulation of the circuit set-up of new calls and the channel access of data users of the VCRMA protocol. The performance of the M-MCMA protocol was studied with different values of number of subslots serve for reservations in each reservation period. Although it is a modified version of the Centralized Minipacket Competition Multiple Access protocol (C-MCMA), it is actually a new control strategy for multiple access of data users. A rule-based control is used to make the throughput of data be maintained at the capacity level when the offered traffic is high than that. The M-MCMA protocol has a very special ability: it can estimate the number of accessing data users at each moment and so the total offered traffic. This ability of the protocol can be used to effectively support the Dynamic Channel Allocation (DCA) in the cellular system. Based on the abilities of the M-MCMA protocol, the new concept “intelligent cellular system” can be developed.

Preface

This combination of papers includes the graduation work of the author in the period February 1996 - February 1997 at the Telecommunications and Traffic-Control Systems Group of the Delft University of Technology, the Netherlands. Although the original assignment was about a protocol for mixed voice/data indoor radio communications, the author has tried to meet the objectives of the third generation communication systems and to make his protocol usable for both indoor and outdoor communications.

Although more works must be done in the studied of the Virtual Circuit Reservation Multiple Access protocol (VCRMA), its performance is very stable and can be easily calculated. The data throughput expressed as a fraction of the free capacity that not used for voice traffic or for system administration is nearly independent of the number of data users and the intensity of voice traffic provided the offered data traffic is high enough. Thanks to the implicit reservation mechanism, the data throughput is getting higher when the data sources have a less bursty character.

The author would like to thank Prof.Dr.Ramjee Prasad and Ir.Jos A.M.Nijhof for their kindness and their supervision. The achievement of the author, despite it is great or tiny, is thanks to his oldest brother Thuan N.Pham and his girl friend Jannie Kaminga who have made the study of the author in the Netherlands come true and supported the author with all their abilities. Finally, the author would like to thank his wife and his child for their encourage and patiently waiting during his study.

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Abstract: Virtual Circuit Reservation Multiple Access protocol (VCRMA) is a hybrid protocol for mixed voice/data radio transmissions. It uses circuit-switched mode for voice and Modified Minipacket Competition Multiple Access (M-MCMA) for data. The VCRMA protocol can be used in all three types of cells: pico-, micro- and macro-. The total throughput of the system with VCRMA protocol depends on the intensity of voice traffic and the character of data sources. The worst case throughput of coded data when all of the user stations send only one data packet per each channel access and there is no voice traffic may be up to about 50% in pico-cell and about 40% in micro-cell. Those values becomes 62% and 54% respectively when the data to be send each time has the length of that of an ATM-cell.

Keywords: Multiple access, circuit reservation, mixed voice/data radio communications.

I. INTRODUCTION

The last decade characterizes it by the growth of the information technology. Beside telephony and data communications, there are coming up more and more new multimedia applications. With the growing demand in communications and mobility, radio techniques are stimulated and merging with each other. People want not only every where to be reachable, but also with the same apparatus they can use more and more applications. Under such a circumstances, radio engineers have tried to develop the third generation of telecommunication systems in which radio channels and apparatus are used not for each application separately, but commonly for several applications.

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On the way to the third generation of the communication systems, there have been proposed many protocols for mixed voice/data radio communications such as Packet Reservation Multiple Access (PRMA) [1,2] and its versions [3,4]. Those protocols use an information packet as a reservation and they can be grouped into the Packet Reservation family. With a protocol of that family, the users get right to use the reserved channel (slot) from the moment that their first packet was successfully received by the central station until they have left it empty. There have been done many works on the Packet Reservation protocols, but the analyses were mainly based on the characteristics of the human speech with an activity ratio (or duty cycle) of about 0.45 and the on-duration of about 1 or 1.4 second [3-7]. For data, the characteristics of the sources are not known very well, but it is possible that they are totally different from that of speech.

Another manner of reservations for speech users is the circuit-switched mode. The channel (or slot) is reserved during entire conversation, but not only during the talk-spurts. This manner of reservation was used to form another protocol for mixed voice/data radio communications at the Delft University of Technology. The protocol was named Circuit Reservation Multiple Access protocol (CRMA) [8-9]. CRMA used the circuit-switched mode for voice and Slotted ALOHA for data. Due to the use of the S-ALOHA, the efficiency in using free capacity, which not used for voice or for system administration, was not high. In order to improve the system performance, a new protocol with the name Modified Minipacket Competition Multiple Access (M-MCMA) was proposed [10]. The M-MCMA protocol is used to replace the S-ALOHA in regulating the circuit set-up of the speech users and the channel access of the data users. There were proposed several versions of the CRMA protocol. Those are grouped into the Circuit Reservation family. In this paper, a version with the name Virtual Circuit Reservation Multiple Access protocol (VCRMA) is shown. The VCRMA protocol is proposed for low gross rate of speech of about 13 Kbps and high channel rate of about 2Mbps.

This paper is organised as follows: Section II gives the organisational aspects of the VCRMA protocol. Timing of the slots which affect mainly the system throughput are also shown there. Discussions about the ways to achieve the virtual concept of the VCRMA protocol are given in Section III. Simulations results are shown in Section IV. Comparisons of simulation results with those of calculations are given in Section V. Finally, conclusions and recommendations are given in Section VI.

II. VIRTUAL CIRCUIT RESERVATION MULTIPLE ACCESS PROTOCOL (VCRMA)

Virtual Circuit Reservation Multiple Access protocol (VCRMA) is a hybrid protocol. It uses circuit-switched mode for voice and Modified Minipacket Competition Multiple Access (M-MCMA) [10] for data. With the circuit-switched mode, the speech users need to access the common channel only once to set-up the circuit at the beginning of their conversations. The circuit is reserved for them during entire their conversation. This mode of the speech service is a traditional one used for a long time in the telephony. It has been considered as a wasting mode of service, because it wastes a part of the system capacity due to the idle time of the principal pauses of the speech. The protocols of the Circuit Reservation family use the circuit switched mode for voice, but during the principal pauses of the talks, the free capacity is used for data transmission. In this manner, the speech quality is not degraded due to the service of the system and the system capacity is used rather effectively.

With the most protocols of the Circuit Reservation family, the central station (named Group Base Station (GBS)) must wait for a duration of *2.a*, where *a* is the worst case propagation delay, in order to ensure a reserved slot is temporally free before using that slot for data transmission. Until now, the protocols of the Circuit Reservation family use Time Division Duplexing (TDD) in order to improved performance when the offered traffic is temporally asymmetric. The VCRMA protocol differs from other protocols of its family by the way of ensuring if a particular reserved slot is temporally free. Without waiting for the duration of *2.a* from the beginning of the slot, the protocol makes the circuit become virtual what explains the name of the protocol.

With the VCRMA protocol, the M-MCMA protocol controls not only the channel access of the data users, but also that for circuit set-up of the speech users. With the slot duration version of the M-MCMA protocol, slots can be divided into two types: reservation slot (R-slot) and information slot (I-slot). The information slots, in turn, are divided into assignment slots (ASS-slots) and down-link slots (DL-slots). Each R-slot begins with a broadcast command (BRO) to inform the users about sending their reservations and to give them a permission probability with which the users can send their reservations if they have packet(s) to transmit.

The frame structure of the VCRMA protocol is shown in Fig.1. In that figure, SYN-slot is the slot for frequency and time synchronisation. In that slot, the group base station (GBS) send a patron that is fixed and known to the users beside other system identification information. SR-slot is a special reservation slot which serves for reservation sending of the new calls and of the data users which has a data rate greater than about 50 Kpbs. Short delay message (SDM) may be permitted to use this slot. P/A-slot is a slot for paging and address getting. All of the non-active users must listen to this slot. The slot is a paging or an address getting slot depends on the command that is sent by the GBS at its beginning. SR-ack-slot and P-ack-slot are slots that serve for acknowledgements about successful reservations in the SR-slot and for answering the paging signal respectively. If the foregoing P/A-slot in the frame was an address getting slot, the P-ack-slot will become an address getting slot.

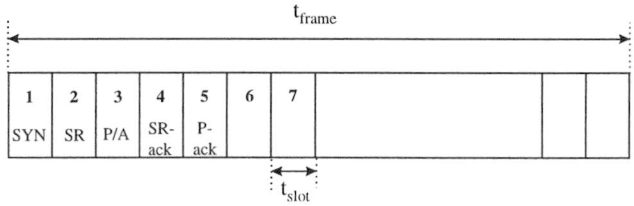

Fig.1: The frame structure of the VCRMA protocol.

The VCRMA protocol uses a map for the identification numbers (ID's) and addresses. At the first channel access, user-stations send an arbitrary number of 9 bits as their ID. The GBS will give them another ID for temporal using. The next packet that will be sent by the reserving user contains his true ID, class of service, destination address, etc. After checking the right authentication of that user, the GBS will give him a communication code coded by his own secrete communication key. The user decodes the packet and get the communication code. Thereafter, all of the packets sent by that user are coded information packets without addresses.

In that manner, the addresses will not be sent in each packet. That improves the efficiency in the transmission of users-information. Besides, the user-information is protected and therefore the privacy is improved. To protect user-information again random errors or short burst-errors due to transmission, a Forward Error Correction (FEC) code with a code rate of about ½ may be used.

Beside the slots shown in Fig.1, there are other slots with the names ASS-slot, R-slot, FREE-slot and DL-slot. An

ASS-slot is a slot where the right to use the rest of the slot is given to a reserving data user-station. After receiving an ASS-command, the station with the ID in the command will send its data packet and will receive an acknowledgement in the next R-slot or ASS-slot. The R-slot is a slot for reservations of other data users which have no right to use the SR-slot. The R-slot has the same structure as the SR-slot, but its position is not fixed. The FREE-slot is a slot where the users can send their data packet directly if they have already got an temporal ID from the GBS. The introduction of this type of slots makes protocol more complex and it may be omitted. It is optional and its use is the result of the trade-off between complexity and effectivity of the system. The DL-slot is a slot with a down-link data packet. The GBS can get an acknowledgement at the end of the slot if the processing time before sending an acknowledgement is small. Otherwise, the GBS will get acknowledgements of the DL-packets through the acknowledgement request slot (ACK-Q-slot). The structure of the ACK-Q-slot is the same as that of the R-slot, except that it begins with an acknowledgement request command. The position of the subslot where the data users can send their ARQ's (AutoRepeat reQuests) or acknowledgements is specified in the DL-packet. Timing of the SR-slot, ASS-slot, FREE-slot and DL-slot are shown in Figs.2-5 respectively. For the shake of simplicity, only the case when the user terminals are at the boundary of the cell are drawn in the figures. The calculations in this paper are also done for this case.

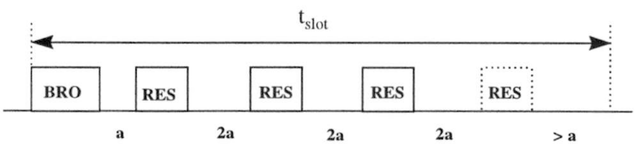

Fig.2. Timing of the (S)R-slot of the V-CRMA protocol.

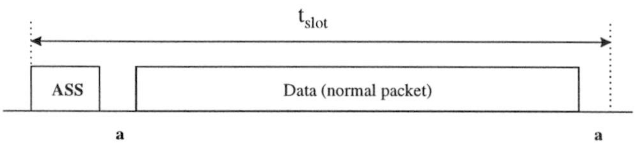

Fig.3. Timing of an ASS-slot of the V-CRMA protocol.

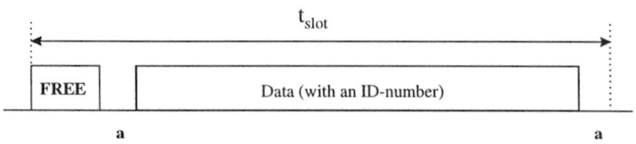

Fig.4. Timing of a FREE-slot of the V-CRMA protocol.

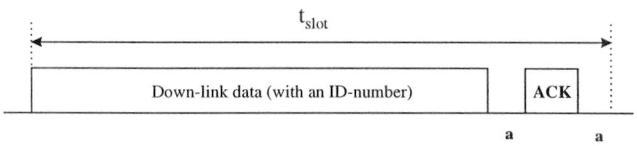

Fig.5. Timing of a down link-slot of the V-CRMA protocol.

The number of slots per frame of the VCRMA protocol depends on the channel rate and the structure of the speech packet. In order to improve the reliability in speech service, the recommended number of training sequences in each speech packet is two. When the channel rate is 2 Mbps, the number of slots per frame is 104 in a pico cell (or micro cell).

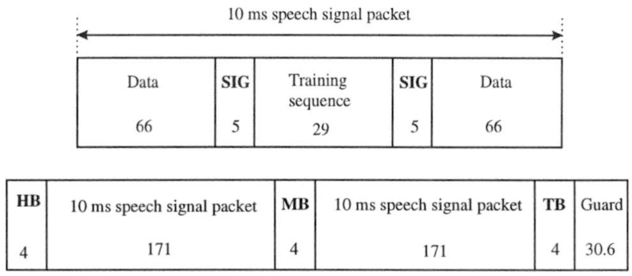

Fig.6: Structure of the voice packets used in the VCRMA protocol.

The structure of a voice packet of the VCRMA protocol is shown in Fig.6. In that figure, HB and TB are head bits and tail bits respectively. They serve as stuff-bits for power up and down at the beginning and the end of each packet in order to limit the bandwidth due to non-continuity of the transmissions. Training sequence serves for channel estimation and equalisation in receiver. SIG can be regarded as stuff-bits in order easily to differentiate the training sequence from the data. MB is mid-bits which serve for easy differentiating two data sequences.

TABLE I
Specifications of the PRMA++ and VCRMA protocols in pico- and micro-cells.

Aspect	PRMA++	VCRMA
channel rate	1.8 Mbps	2.0 Mbps
frame duration	5 ms	20 ms
slot duration	ca. 70 μs	ca. 192 μs
number of slots per frame	72	104
duplexing	FDD/ optional TDD	TDD
power control	yes	yes
timing advance	yes	no

The main specifications of the VCRMA protocol in pico- and micro-cell are given in Table I. In that table, there are also given the main specifications of the PRMA++ (Packet Reservation Multiple Access plus plus) protocol which is the most elegant one of the Packet Reservation family [11-17].

TABLE II
Specifications of the VCRMA protocol for three types of cells.

	pico-cell	micro-cell	macro-cell
channel rate	2.0 Mbps	2.0 Mbps	500 Kbps
worst case delay	2 μs	8 μs	32 μs
maximum radius	400 m	1.8 Km	7.2 Km
frame duration	20 ms	20 ms	20 ms
slot duration	ca. 192 μs	ca. 192 μs	ca. 768 μs
number of slots per frame	104	104	26
number of slots lost due to administration	5	5	5
type of duplexing	TDD	TDD	TDD
number of simultaneous conversations	49	49	10
number of data sending stations	> 120	> 120	> 120

TABLE III
Length of coded information in different types of slots of the VCRMA protocol and the throughput of those slots in a pico-cell.

slot type	length of the coded information [bits]	total length needed [bits]	throughput of information packet [%]	throughput of coded information [%]
(S)R-	0	356	0	0
ASS-	326	384	87.36	84.76
FREE-	326	384	93.60	84.76
DL-	326	384	93.60	84.76
speech	264	362	92.04	68.64

TABLE IV
Length of coded information in different types of slots of the VCRMA protocol and the throughput of those slots in a micro- or macro-cell.

slot type	length of the coded information [bits]	total length needed [bits]	throughput of information packet [%]	throughput of coded information [%]
(S)R-	0	368	0	0
ASS-	302	384	81.12	78.52
FREE-	302	384	87.36	78.52
DL-	302	384	87.36	78.52
speech	264	386	92.04	68.64

The VCRMA protocol differs from the well-known protocols by its reservation mechanism. It uses not only the explicit reservation mechanism through the M-MCMA protocol, but also an implicit reservation mechanism through the so-called Continuity Indicator (CI). CI is a bit at the end of each up-link data packet. It informs the GBS about if the terminal (VBR) still has another packet to transmit. In this manner, the data throughput can be improved when the data sources have a less bursty character, i.e. when the VBR's access the common channel in order to send more than one data packet, because the percentage of the needed R-slots can be reduced in that situation.

The channel rate and other specifications of the VCRMA protocol in all three types of cells are shown in Table II. For calculations of throughput of coded data, it is assumed that the FEC code used in the reservation packets is able to combat the channel impairment. When the length of each reservation packet is 32 bits, the length in bits of the data part and of the data packet for different types of slots in a pico-cell are shown in Table III. The throughput of coded data is also shown there. Those values when the VCRMA protocol is used in a micro-cell or in a macro-cell are shown in Table IV. From that table, it is seen that the length in bits needed for the slot with a speech packet is 386 bits which is nearly 2 bits longer than the slot duration. Actually, there is no problem with the integrity of the packets due to that fact, because each packet begins and ends with the stuff-bits for power up and down.

Because the VCRMA uses not only an explicit reservation mechanism through the M-MCMA protocol, but also an implicit reservation through the Continue Indicator bit at the end of each up-link packet, the data throughput of the protocol depend on the character of the data sources. The data throughput is expected to be higher when the data sources has a less bursty character. For calculations of the throughput, it is handy to introduce a parameter with the name continuity ratio (CR). CR is defined as an average number of slots needed for data transmissions per each channel access of the users. Clearly, CR is a relative measure, because it depends not only on the character of the data sources, but also, within other things, on the slot duration which, in turn, depends on the channel rate and the trade-offs between the reliability of the speech service and the number of simultaneous conversations that can be served.

As mentioned before, the VCRMA protocol differs from other protocols of its family by the way of ensuring if a particular reserved slot is temporally free. The GBS does not need to wait for a duration of $2.a$ at the beginning of each slot in order to ensure that it is free. That makes the data throughput less sensible to the type of the cell and so the protocol can be used in all three types of cells. With that manner of ensuring if a reserved slot is temporally free, the virtuality of the circuit-switched mode of the Circuit Reservation family has more sense. In next Section, the manners to achieve this virtual concept of the VCRMA protocol will be discussed.

III. DISCUSSIONS

In the foregoing Section, it was mentioned that the VCRMA protocol may have a pretty uniformity in the data throughput for all of the three types of cells: pico-, micro- and macro-, because the GBS does not need to wait for a duration of *2.a* from the beginning of a slot in order to ensure if it is free. The pretty uniform makes the protocol more suitable for the future Universal Mobile Telecommunication System (UMTS) where an umbrella cell structure may be needed. The VCRMA protocol was formed by using the characteristic of the human speech and the fact that the Speech Activity Detector (SAD) is used by the terminals of the speakers [1-2,8].

With the VCRMA protocol, when a reserved slot was left empty in the last frame, the GBS will immediately use it for data transmissions without waiting for a duration of *2.a*. When the voice transmitter owning that reserved slot is again active, collision will occur. There are two ways to implement the VCRMA protocol while maintaining the quality of service for speech: first, using the achievements of the speech coding techniques; or second, making a small modification in the hardware/software of the speech transmitter. Both of these two ways are possible to do and they will not be expensive.

If we look at the protocols of the Packet Reservation family, the front-end clipping phenomenon is reported to have a remarkable effect on the speech perception only if the dropping percentage is greater than about 1% [1]. One of the most recent protocols of that family is the PRMA++ protocol. PRMA++ uses an interleaving of depth four for voice packets. With the average duration of 1.4 s of the talk-spurts and the frame duration of 5 ms, the quality of the speech is not degraded if one or two voice packets were dropped. That means that the speech coding techniques can recover the lost information that has the length up to a half of the interleaving block, which is equivalent to the 10 ms duration of the speech signal.

We return to the VCRMA protocol, the worst case collision occurs when the GBS uses the possibly free slot for down-link data and the speech user who owns that reserved slot is again active. In this case, all of the 20 ms speech information will be lost, which is equal to four packets of the PRMA++ or greater than 1%. This situation can be avoided by limiting the use of the possibly free up-link slots for down-link data or by waiting for a duration of *2.a* in order to ensure that the slot is free. In other cases when the GBS uses the slot as a R-slot, as an ASS-slot or as a FREE-slot, the lost of speech information is just about of duration of 2.5 ms which is equivalent with a half of a voice packet of the PRMA++ protocol. The speech coding techniques will recover the loss information and this situation causes no problems for the perception of the speech. When collision occurred, the GBS will not use that slot until it is empty again.

The second way to implement the VCRMA protocol is to make a small modification in the hardware or software of the speech transmitter so that it will send the first voice packet twice after the SAD has detected a pause. In this manner, the speech quality of a perfect circuit-switched mode for voice is maintained. The average delay of the voice packet is 30 ms if the frame duration is 10 ms, but it is 50 ms when the frame duration is 20 ms. Thus this second way can not be used when the frame duration is 20 ms, because it does not satisfy the specifications of 30 ms for delay in access for speech [3].

For the down-link reserved slots of speech there is no problem. That is because the beginning stuff-bits of the data packets may be made to have a different value than that of a voice packet. Besides, the number of training sequences and the length of coded information in a data packets are different from those of a speech packet. The receiver can easily recognise which packet is not a speech packet and just discards it.

V. SIMULATION RESULTS

Simulations were done with two models of the activity of the speakers. In the first model, the reserved slots are randomly occupied with a probability of 0.45 which corresponds with the on-off durations of the talk-spurts of 1.4 s and 1.7 s respectively. The second model is the Brady model with four states [18]. Due to the fact that the VCRMA protocol uses Time Division Duplexing (TDD), the random occupation of the slot by the speaker with probability of about 0.45 is not very realistic. The more suitable model for two way conversations is the Brady model. The results of those two ways of simulations were the same what means that the performance in the data service of the protocol is not dependent on the speech model.

With the Brady model, there is a situation that both speakers of a conversation are speaking at the same time. That situation was called a double talk by Brady. When the double talk has been occurred for more than a certain time, each speaker will have a tendency to be silent to listen to the other side with a certain probability. Those certain time and certain probability depend on the character of the speaker and his speed of reaction. In the simulations of the VCRMA protocol, that certain time needed for recognition of the double talk is taken equal to the duration of 3 frames and the certain probability that the speaker will be silent when the double talk has been recognized is 0.5. Fig.7 shows the 4-state Brady model for 2-ways conversations. The crossing transition from mutual silent to double talk or inversely is enable in the simulations of the VCRMA protocol. Fig.8 shows the 2-state model for the activity of each speaker when there is no double talk.

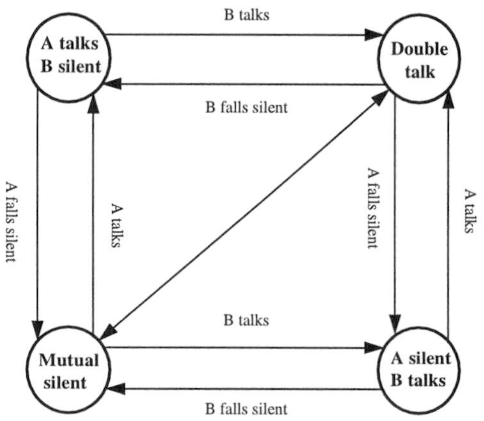

Fig.7. The Brady 4-state model for 2-way conversations with crossing transition used in the simulations of the VCRMA protocol.

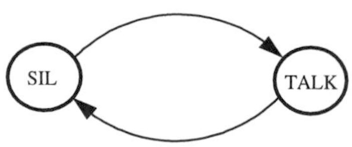

Fig.8. The 2-state model for speech activity of each speaker when they are in conversations.

Simulation process for each value of the packet arrival rate α is shown in Fig.9.

Other parameters used in the simulations and their values are:
- the mean talk-spurt duration is 1.4 s [12];
- the mean duration of the principal pauses is 1.7 s [12];
- the simulation duration is 100, 200 or 1000 frames of 104 slots depends on the value of the continuity ratio CR;
- the number of the administration slots in each frame is 5;
- the number of the simultaneous conversations is 0, or 49 (all of the 98 non-administrative slots are reserved);
- the number of subslots in each reservation slot is from 2 to 9 and mainly 5 and 8;
- the number of the data sending stations (VBR's) is 10, 30, 60 and 120;
- the continuity ratio CR is 1-5, 10 and 20.

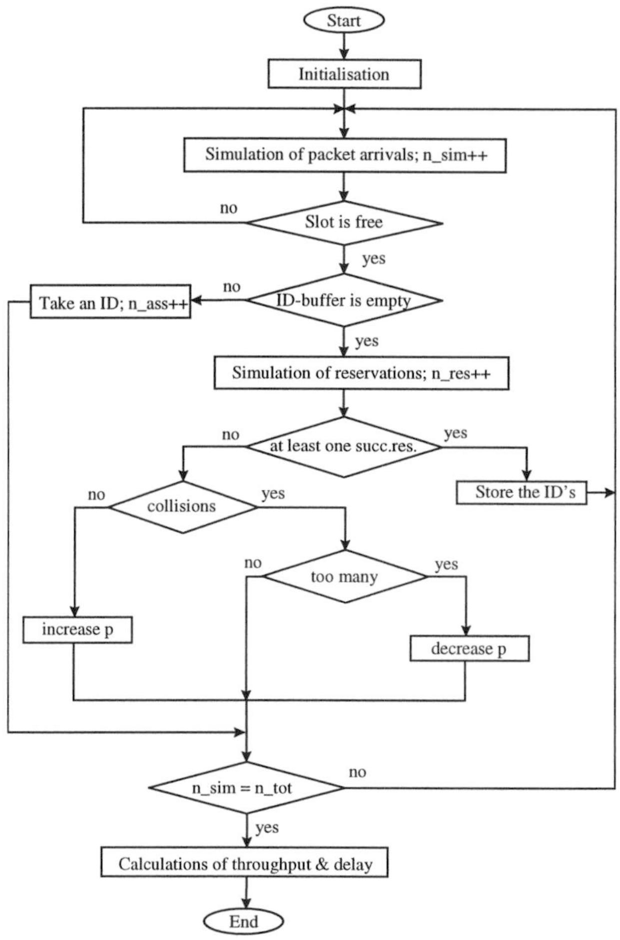

Fig.9. Simulation process of the VCRMA protocol.

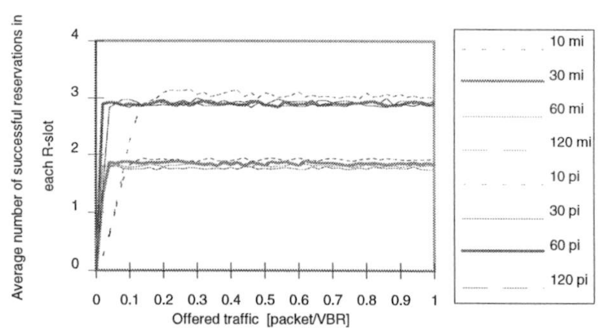

Fig.10. Simulation results of the average number of successful reservations in each R-slot when there is no voice traffic and the number of subslots in each R-slot is 5 and 8.

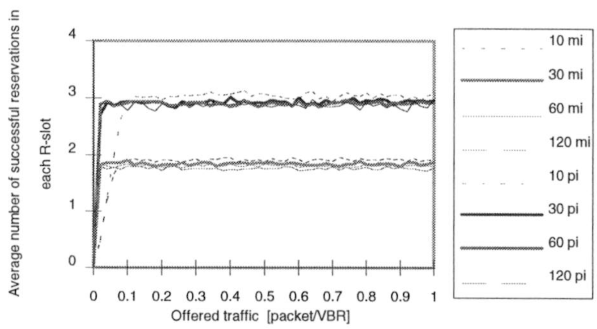

Fig.11. Simulation results of the average number of successful reservations in each R-slot when all of non-administrational slots are reserved by voice traffic and the number of subslots in each R-slot is 5 and 8.

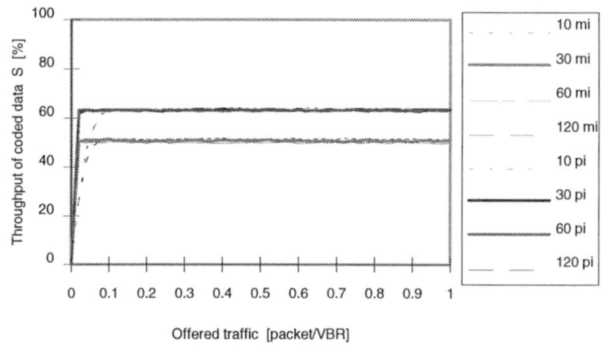

Fig.13. Simulation results of the throughput of coded data when all of non-administrational slots are reserved by voice traffic and the number of subslots in each R-slot is 5 and 8.

Simulation results of the average number of successful reservations are shown in Figs. 10 and 11 for the cases when the number of subslots for reservations in each R-slot is 5 and 8. Fig.10 shows the case when there is no voice traffic at all, while the case when all of the available slots are reserved by voice traffic is shown in Fig.11. In those figures, the continuity ratio CR has a value of one what means that the data sources have a completely bursty character.

From Figs.10-11, it is seen that the average number of the successful reservations in each R-slot is proportional to the number of the subslots for reservations in a R-slot and the average number of the successful reservations per subslot is about 0.37 ± 0.02 thus within 6% from the maximum value of the S-ALOHA. That value is nearly independent of the intensity of the voice traffic or of the character of the data sources what proves the effectiveness of the control mechanism of the VCRMA protocol.

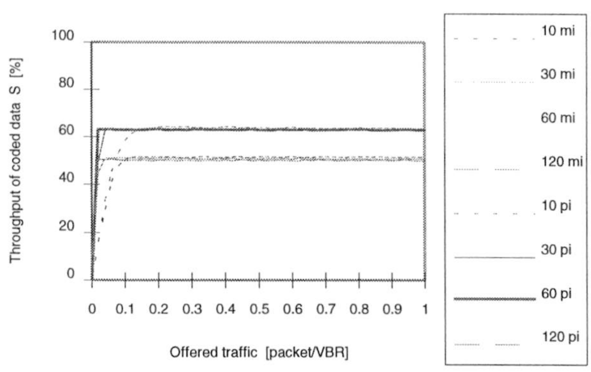

Fig.12. Simulation results of the throughput of coded data when there is no voice traffic and the number of subslots in each R-slot is 5 and 8.

Simulation results of the throughput of coded data expressed as a fraction of the free capacity that not used by voice traffic or for administration are shown in Figs.12 and 13 for the case when the number of subslots for reservations in a R-slot is 5 and 8. In Fig.12 is the throughput in the case when there is no voice traffic and in Fig.13 is that of the case when all of non-administrational slots are reserved by the voice traffic. It is seen from those figures that the throughput of coded data expressed as a fraction of the free capacity is independent of the intensity of the voice traffic and nearly independent of the number of active data users in the cell provided the offered data traffic is high enough.

Analysis and simulation results showed that throughput of the coded data is getting higher when the data sources have a less bursty character. The getting higher of the throughput of the coded data when the data sources have a less bursty character is thanks to the implicit reservation of the protocol so that the percentage of the needed R-slot becomes lower. That will be seen in the next Section.

VI. COMPARISON OF THE SIMULATION RESULTS WITH THOSE OF CALCULATIONS

In [10], it was shown that the average number of successful reservations in each reservation period with 3 subslots for reservations is given by the equation (7)

$$n_{3sts} = N.\,p.(1-p)^{\frac{N}{3}-1} \qquad (1)$$

,where p is the permission probability for sending reservations and N is the number of the data sending stations (named Variable Bit Rate stations (VBR's)). In the ideal case of the control, the probability p will be set to a value of *3/N*. For the active VBR's, its packet arrival rate α is temporally equal to one at the moment of reservation sending. So through the value of the suitable permission probability p, the GBS can estimate the number of active data stations accessing the common channel.

Generalizing equation (1) for the case when there are k subslots for reservations in each R-slot, the number of successful reservations in a R-slot with k subslots is:

$$n_{succ.res.} = N.\, p.\,(1-p)^{\frac{N}{k}-1} \quad , \; k < N \qquad (2)$$

In the ideal case of the control, the permission probability p will have a value of

$$p_{desired} = \frac{k}{N} \qquad (3)$$

Then the average number of the successful reservations is:

$$n_{succ.res.} = N.\frac{k}{N}.(1-\frac{k}{N})^{\frac{N}{k}-1}$$

$$= k.(1-\frac{k}{N})^{\frac{N}{k}-1} \quad , \; k < N \qquad (4)$$

When $k << N$:

$$n_{succ.res.} \cong k.\, e^{-1} \qquad (5)$$

From this approximation we can see that theoretically, the protocol can be used with an unlimited number of data users (VBR's) provided the ideal control so that the permission probability can be set equal to $p_{desired} = k/N$. From equation (5), it is also seen that the greater is the number of subslots k in each R-slot, the higher is the average number of the successful reservations. But there may be difficulty in the maintaining the effectiveness of the control when the number of subslots k is great. Moreover, the number of the subslots for reservations is limited by the slot duration.

For the VCRMA protocol, comparison of the simulation results with those of the analysis is done for the throughput of data, which is calculated from the average number of successful reservations in each R-slot. Delay for data can be just calculated from the offered traffic, the free capacity and the average number of successful reservations in each R-slot using the Little's formula [19, p.501]. So it is not necessary to make a comparison for delay for data.

The theoretical value of the data throughput is calculated by following equation :

$$S_T = \frac{n_{succ.res.} \cdot CR.S_{slot}}{n_{succ.res.} \cdot CR + 1} \qquad (6)$$

,where
- $n_{succ.res.}$ is the number of successful reservations in each R-slot, calculated by equation (5);
- CR is the continuity ratio, which expresses the character of the data sources;
- S_{slot} is the slot throughput i.e. the efficiency in using an information slot for transmission of the coded data. The slot throughput is 84.76% for pico-cell and 78.52% for micro-cell when the frame duration is 20 ms and there are 104 slots in each frame (conf. Tables III-IV);

Throughput of coded data for different values of the continuity ratio is shown in Table V. In that table, it is assumed that the address getting task is taken by the P/A and the P-ack slots. Besides, it is also assumed that there is no voice traffic. When the losses due to the training sequence and the control field are taken into account, the throughput becomes smaller. The throughput in this case is shown in Table VI.

From the Tables IV-VI, it may be wondered why the data throughput in a macro-cell is much lower than that in a micro-cell while their slot throughputs are the same. That is because the number of slots per frame in a macro-cell is only 26 and the number of administration slots is 5. That means that about 20% of the channel capacity is lost. Thus in order to improve efficiency in macro-cells, that number of the administration slots must be reduced by scheduling them in 2 or 3 slots.

TABLE V
Throughput of coded information of the VCRMA protocol with different values of the continuity ratio (CR) when the losses due to the training sequence and control field are not taken into account.

CR ratio	length of the coded information to transmit in pico-/micro-cell [bytes]	throughput of the coded information in a pico-cell	throughput of the coded information in a micro-cell	throughput of the coded information in a macro-cell
1	41/38	0.606	0.487	0.414
2	82/76	0.694	0.592	0.502
3	123/114	0.729	0.637	0.540
4	164/152	0.748	0.662	0.562
5	205/190	0.760	0.679	0.576
10	410/380	0.785	0.714	0.605
20	820/760	0.798	0.732	0.622

TABLE VI
Throughput of coded information of the VCRMA protocol with different values of the continuity ratio (CR) when the losses due to the training sequence and control field are taken into account.

CR ratio	length of the coded information to transmit in pico-/micro-cell [bytes]	throughput of the coded information in a pico-cell	throughput of the coded information in a micro-cell	throughput of the coded information in a macro-cell
1	34/31	0.503	0.398	0.337
2	68/62	0.575	0.483	0.410
3	102/93	0.605	0.520	0.441
4	136/124	0.621	0.540	0.458
5	170/155	0.630	0.554	0.470
10	340/310	0.651	0.582	0.494
20	680/620	0.662	0.598	0.507

The simulation throughput is calculated by following equation :

$$S_s = \frac{n_{ass} \cdot S_{slot}}{n_{free}} \quad (7)$$

,where
- n_{free} is the number of the free slot that not used by the voice traffic or for administration such as for call set-up, paging, acknowledgement for these set-up or paging, etc.
- n_{ass} is the number of the assigning slots, i.e. the number of information slots in data transmission of the up-link.

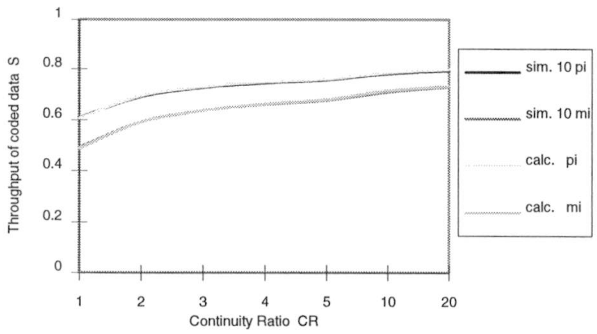

Fig.14. Comparison of the simulated throughput of coded data with that of calculations when the number VBR's is 10 and the number of subslots for reservations in each R-slot is 5 and 8.

Fig.14 shows the comparison of the analysis and simulations in term of the throughput of the coded data, expressed as a fraction of the free capacity, for pico- and micro-cell when the number of active data users is 10. The comparison for the case when the number of active data users is 120 is shown in Fig.15.

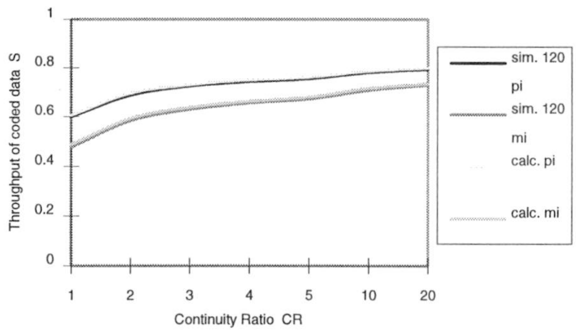

Fig.15. Comparison of the simulated throughput of coded data with that of calculations when the number VBR's is 120 and the number of subslots for reservations in each R-slot is 5 and 8.

It is seen from Figs.14-15 that analysis and simulation results are nearly perfectly matched with each other when equation (5) is used for calculations of the average number of successful reservations in each R-slot. Thus that equation can be used for design of the protocols which use the control mechanism of the VCRMA (or of the M-MCMA) protocol. The rule of thumb is that the average number of successful reservations in each subslot is 0.37$\pm$0.02 which is within 6% from e^{-1}.

In order to see the efficiency of the whole protocol, the total system throughput of the VCRMA protocol is calculated and drawn in Fig.16 as a function of the number of simultaneous conversations. Due to the fact that the protocol use TDD, two slots are needed for each conversation. The total system throughput *TST* is calculated by following equation

$$TST = \frac{n_{conv} \cdot \left[AR_{sp} \cdot S_{sp} + (1 - AR_{sp}) \cdot S_d\right]}{n_{sl}} + \frac{(n_{sl} - n_{adm} - n_{conv}) \cdot S_d}{n_{sl}} \quad (8)$$

,where
- n_{conv} is the number slots used for conversations;
- AR_{sp} =0.45 is activity ratio of the human speech [12];
- S_{sp} is the efficiency in using a slot for coded speech signal;
- S_d is the throughput of coded data;
- n_{sl} is the number of slots per frame;
- n_{adm} is the number of administration slots per frame.

In Fig.16, it is assumed that the offered data traffic is high enough to use all of the free capacity. The continuity ratio of the data sources is taken equal to four what means the users access the common channel for sending four data packets each time. It is equivalent to the fact that the data to be sent each time has the length of an ATM cell when the FEC code with code rate of about ½ is used. In calculations of total system throughput drawn in Fig.16, the losses due to control field and the training sequence are already taken into account. From that figure, it is seen that although the total system throughput of the VCRMA protocol in macro cells is not very high, the protocol still can be used for all three types of cells.

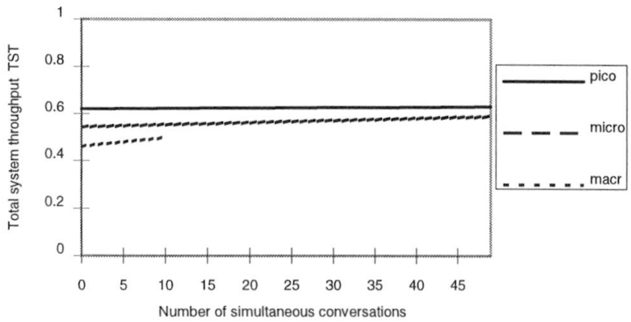

Fig.16 Total system throughput of the VCRMA protocol as a function of the number of simultaneous conversations when the data to be sent each time has the length of that of an ATM cell.

VI. CONCLUSIONS AND RECOMMENDATIONS

In this paper, a new protocol for mixed voice/data radio communications with the name Virtual Circuit Reservation Multiple Access (VCRMA) is introduced. This protocol is proposed for the system with low gross speech rate of about 13 Kbps and therefore it will be suitable with the trend in development of communication systems. Although the performance of the protocol for macro-cell is lower than that of micro- or pico-cell, the protocol still can be used for future Universal Mobile Telecommunication Systems (UMTS), because it is rather high and stable. The necessary system parameters can be sent in the SYN-packet from the GBS, so there will be no problem with the uniformity of the protocol.

The ways to implement the virtual concept of the protocol have been discussed in Section III. The second way of modifying software or hardware of the transmitter perfectly maintains the speech quality of the circuit-switched mode, but it is only suitable when the frame duration is not longer than 10 ms. The first way of using achievements of the speech coding techniques is preferred in the implementation of the protocol. The degradation in the speech quality due to possible collisions at the beginning of the talk-spurts is expected to be not remarkable.

The performance of the Virtual Circuit Reservation Multiple Access protocol (VCRMA) is shown through the analysis of average number of successful reservations in each R-slot and through the comparison of the analysis with simulation results in term of the throughput of the coded data expressed as a fraction of the free capacity that not used by voice traffic or used for the administration of the system. The simulation results match nearly perfectly with those of the calculations when equation (5) is used.

The average number of the successful reservations in each R-slot is nearly independent of the character of the data sources, the number of active data user stations in the cell and the intensity of voice traffic. A rule of thumb for design of the protocols which use the control mechanism of the VCRMA protocol is as followed: when the offered data traffic is high enough, the average number of the successful reservations per each subslots which serve for reservations is within the range 0.37 ± 0.02.

Theoretically, the VCRMA protocol can be used with an unlimited number of the data users stations. Throughput of coded data, expressed as a fraction of the free capacity, is nearly independent of the intensity of the voice traffic and the number of data user stations. Thanks to the implicit reservation mechanism of the protocol, the data throughput becomes higher when the data sources have a less bursty character. The worst case throughput when the data sources are completely bursty is about 50% for pico-cell and about 40% for micro-cell when the losses due to the equalisation and the control field are taken into account. Those values were calculated with the assumption that the FEC code used for error correction is able to combat the effects of channel impairness on the integrity of the reservation packets. Besides, the processing time before sending an acknowledgement ACK when training sequence is used for channel equalisation was not taken into account. Further studies are recommended in those two directions.

The VCRMA protocol can be used with large number of data users, but in order to limit delay for data when the total offered traffic is greater than the system capacity, the use of the Dynamic Channel Allocation (DCA) is recommended. The VCRMA can then effectively support the DCA through the ability in estimation of the total offered traffic of the M-MCMA protocol. Through this ability, the VCRMA protocol can also be used for the new intelligent cellular system [10].

When the channel rate is 2 Mbps, the VCRMA protocol can simultaneously serve 49 conversations in circuit-switched mode and more than 120 active data user stations. That ability makes the protocol very effective in the environment that has a great demand in data communications such as office or industry. For mobile communications, the VCRMA protocol is not very suitable at this moment, because the need in data communications is still low. But it is expected in the near future, when there are more multimedia applications, the protocol can be one of the strong candidate for future systems.

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Modified Minipacket Competition Multiple Access protocol

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Abstract: Modified Minipacket Competition Multiple Access (M-MCMA) is proposed as a protocol for wireless communications. M-MCMA is a very powerful protocol. It can be used not only for data alone, but also for mixed voice/data. With this protocol, the problem of choosing the probability with which the user stations send their reservations or data packets is avoided. In this paper, the case of using M-MCMA for data communications alone is shown. Simulation results showed that the data throughput can be up to 85%. The expected throughput is easily calculated and it matches nicely with that of the simulations. Thanks to the rule-based control, the throughput is maintained at the capacity level when the offered traffic is higher than the capacity.

Key words: Multiple access, wireless data communications, rule-based control.

1. INTRODUCTION

In the last decade, there have been developed many protocols for wireless data communications such as Inhibit Sense Multiple Access (ISMA) [1,2], Minipacket Competition Multiple Access (MCMA) [3,4], etc.. Those protocols have a better performance in comparison with the Slotted-ALOHA. Unfortunately, the performance of those protocols is still degraded when the total offered traffic is greater than a certain value specific for a particular protocol. Besides, the choice of the probability with which the user stations will send their reservations or their packets remains a great problem for design engineers, because the offered traffic changes continuously with the time. It depends not only on the number of the user stations, but also on the character of the data sources. If the stations can send their packets at the beginning of every slot when they have packet(s) to transmit, as in the case of the *1*-persistent protocols, the throughput is first fast increased and then fast decreased as the offered traffic becomes higher. If the stations must wait for a random time when the common channel is not available at the time it is sensed, as in the case of the *non*-persistent protocols, the throughput is low at not very high offered traffic. The *p*-persistent protocols may have the throughput between those of the *1*-persistent and non-persistent versions, but the proper choice of the transmission probability in order to use the resources effectively and to meet the fast growing traffic demand is very difficult to make.

In order to improve the robustness of the throughput when the offered traffic is high while maintaining the effectiveness in using the resources when the offered traffic is not very high, a new control strategy with the name Modified Minipacket Competition Multiple Access protocol (M-MCMA) has been proposed. This control strategy is very attractive. It can be used not only for data communication alone, but also for mixed voice/data. Although at the first sight the protocol seems to be complex, its implementation in both hardware and software is expected not difficult to do and not to be too expensive in comparison with that of other protocols. The exact analysis of the M-MCMA protocol when the offered traffic is higher than the capacity may not be carried out, but the expected performance can be seen very easily through calculations. The great advantage of the M-MCMA protocol is that the throughput is maintained at the capacity level despite how higher is the total offered traffic than the system capacity. Moreover, the offered traffic is easily estimated what supports very effectively the use of the Dynamic Channel Allocation (DCA).

In this paper, the case of using the protocol for data communications alone is shown. For the shake of simplicity, only the case when the user terminal is at the boundary of the cell is drawn in the figures. The calculations are also done for that case. Section 2 gives a brief description of the Centralized Minipacket Competition Multiple Access protocol (C-MCMA) from which the Modified Minipacket Competition Multiple Access protocol (M-MCMA) was formed. Sections 3 introduces the M-MCMA protocol and its working. The use of the M-MCMA for data communication alone is described in more details in Section 4. The simulation results for that case are shown in Section 5. Finally, the conclusions are given in Section 6.

2. CENTRALIZED MINIPACKET COMPETITION MULTIPLE ACCESS PROTOCOL (C-MCMA)

Before we go to the modified version, it is necessary to talk about the original one first. The Centralized Minipacket Competition Multiple Access protocol (C-MCMA) was proposed by J.L.Sobrinho *et al.* [3]. C-MCMA uses Time Division Duplexing (TDD) in order to improve the performance when traffic is asymmetric. It is a protocol for wireless local networks and due to the fact that the slot duration is varied, it is usable for data communications alone.

With the C-MCMA, the central station takes the control of the whole cell. It sends a TRY-command to inform the user stations that they can send their minipackets if they have a packet to transmit. When the central station has just successfully received a minipacket, it sends a STOP-command to give permission to transmit the rest of the packet to the station that has the just successfully received minipacket. Otherwise, the TRY-command will be sent. The timings of a minislot with collision and of an idle minislot are shown in Fig.1. Fig.2 shows the timing of the slot with successful transmission. In Figs.1-2, *a'* is the worst case propagation delay.

The data throughput of the C-MCMA protocol, which is defined as the fraction of time used to send the data packets, is calculated via equation [3]

$$S=\frac{t.p_s}{t_{1/\gamma}.p_s+(1-p_s).t_\beta}=\frac{\gamma}{1+(p_s^{-1}-1).\beta.\gamma} \tag{1}$$

,where

- t is the time needed for transmission of the whole data packet;

- $t_{1/\gamma}$ is the duration of the slot with successful transmission;

- t_β is the duration of the idle minislot or of the minislot with collision;

- p_s is the probability that the minipacket is successfully received by the central station;

$$\gamma = t / t_{1/\gamma} \qquad \text{and} \qquad \beta = t_{emp}/t = t_{coll}/t = t_\beta / t$$

If the arrival of the data packets has a Poisson distribution, the capacity of the C-MCMA protocol is then [3]

$$C = \frac{\gamma}{1 + (e-1).\beta.\gamma} \tag{2}$$

Actually, after the duration of a round-trip propagation delay, the central station is already able to recognize if a minislot is an idle one. Thus the normalized duration of an idle slot can be reduced to β-w, where w is the length of the minipacket normalized to that of the data packet. So the throughput of the C-MCMA protocol becomes

$$S_{improved} = \frac{t.p_s}{t_{1/\gamma}.p_s + p_{coll}.t_\beta + p_{emp}.t_{emp}}$$

$$= \frac{\gamma}{1 + p_{coll} \cdot p_s^{-1} . \beta . \gamma + p_{emp} \cdot p_s^{-1} . (\beta - w) . \gamma} \qquad (3)$$

,where p_{coll} is the probability that a collision occurred in the minislot and p_{emp} is the probability that the minislot is an idle one. The capacity is then

$$C_{improved} = \frac{\gamma}{1 + (e-1) . \beta . \gamma - w . \gamma} \qquad (4)$$

In order to see the effects of the worst case propagation delay and channel rate on the C-MCMA protocol, the capacity of both original and improved versions are calculated and shown in Table I. In this table, a is the worst case propagation delay and R is the channel rate. The average length of the data packets used in the calculations is 1000 bits, the number of users is 30 and the packet arrival is assumed to be geometrically distributed. Fig.3 shows the calculated throughput of both original and improved versions of the C-MCMA protocol for the case when the normalized propagation delay a is 0.006, the normalized minipacket length w is 0.025 and the average packet length is 1000 bits. The calculations were done by using equations (1) and (3) and the assumption that the data arrival rate has a Poisson distribution.

The C-MCMA protocol has an advantage that the losses due to the collisions or emptiness are reduced, but the control is not adaptive, therefore the throughput is still sensible to the intensity of the offered traffic. From Table I and Fig.3 it is seen that although the capacity of the C-MCMA is high, the throughput is still decreased when the offered traffic is higher than a certain value. That certain value depends on which persistence is used, but there is always disadvantage. If the *1*-persistent version is used, the throughput of the C-MCMA will be first fast increased and then fast decreased with the increase of the offered traffic. If a *non*-persistent version is used, the throughput will be low at the not very high offered traffic. The *p*-persistent version may have the throughput between those of the *1*-persistent and *non*-persistent versions, but the choice of the probability *p* with which the users will send their packets is still a great problem for the design engineers. This problem can be avoided with the modified version of the C-MCMA protocol with the name Modified Minipacket Competition Multiple Access protocol which is described in the next section.

3. MODIFIED MINIPACKET COMPETITION MULTIPLE ACCESS PROTOCOL (M-MCMA)

The Modified Minipacket Competition Multiple Access protocol (M-MCMA) was first proposed for using in mixed voice/data radio communications. The main idea of the M-MCMA protocol is to make the offered traffic so that it is virtually approximately equal to the number of the subtime slots that serve for reservations, despite of the actual value of the offered traffic provided that the latter is greater than the number of the subtime slots. M-MCMA not only plays an important role in the coordination of the channel access in the protocols with the circuit-switched mode for speech service, but also may be used alone or in combination with other protocols to form the hybrid ones. In this section, first the description of the M-MCMA protocol and its control mechanism are given, then the theoretical foundation of the M-MCMA and the analysis of success of the control are shown.

3.1. Description of the M-MCMA protocol

Although the M-MCMA protocol is a modified version of the Centralized Minipacket Competition Multiple Access protocol (C-MCMA), it was first proposed for using with mixed voice/data radio communications and therefore the terminology used in the M-MCMA is different from that of the C-MCMA protocol. With the M-MCMA protocol, the central station is named Group Base Station (GBS). The user stations which have data packets to transmit are called the Variable Bit Rate stations (VBR-stations or VBR's) and the user stations which have voice packets to transmit is called the Constant Bit Rate stations (CBR-stations or CBR's).

M-MCMA is a modified version of the C-MCMA protocol in the sense that the VBR-stations use their identification number (ID-number) instead of the beginning part of a packet for contending the use of the channel and the rule-based control is used for changing the permission probability. With the M-MCMA protocol, the VBR-stations with packet(s) to transmit may send their ID-numbers not immediately after receiving a broadcast command from the GBS. They may send their reservations randomly in one of the k consecutive subtime slots which serve for the reservations, where k is an arbitrary positive integer number. A reservation is considered to be successful if there were no other reservations in the same subtime slot. Collision takes place when there are two or more reservations in the same subtime slot.

The M-MCMA protocol uses a centralized control and that control is taken by the GBS. Through the number of the successfully received reservations, the GBS estimates the number of active data stations and changes the permission probabilities p_{per} when necessary. The probability p_{per} is the probability with which a VBR-station will send its reservation when it has a packet to transmit. It is set higher when all of the k subtime slots were left empty and it will be set lower when collisions occur in all of those k subtime slots.

The GBS does not need to contend with the VBR's for using the common radio channel. It will take a priority to transmit its packets once in m times, where m is an integer between 2 and the number of VBR's in the cell plus one. The value of the parameter m is set to a suitable value by the GBS estimating the number of active data stations through the permission probability p_{per}. Thus the protocol is pretty fair.

The situation when there were no successfully received reservations or there was no reservation at all is shown in Fig.4. For the sake of simplicity, the case $k=3$ is drawn in the figures. Such a slot is called a missing slot. The timing of a normal slot when there is at least one successful reservation in the k subtime slots is shown in Fig.5. In this figure, an acknowledgement ACK is combined with the broadcast BRO as in the case of the C-MCMA protocol. That makes the throughput a little higher than the case when the acknowledgement is sent separately. In Fig. 6 is the situation when the GBS transmits its packet or it assigns the use of the channel to the VBR that has a successfully received reservation in the last one (or more) slot(s) but has not received a permission to transmit yet. That slot is called an assigning slot.

In Figs. 4-6, a is the worst case propagation delay in the cell, BRO is a broadcast command which informs the VBR's about sending their reservations and gives the probability p_{per} with which the VBR's will send their reservations. RES is a reservation of a VBR and it contains at least three parts: ID-number of the VBR, ID-check bit(s) and priority. The priority of each VBR is not important when the M-MCMA protocol is used for data transmissions alone, but it may be important in the case of mixed voice/data transmissions. ASS is an assignment command which gives permission to one of the VBR's or just inhibits them in the case that the GBS sends its packet.

The ASS-command may consist of three parts: an assignment itself, the ID-number of the VBR that gets the right to use the channel and the ID-number check bits. The structures of a broadcast command BRO, a reservation RES and an ASS-command are given in Fig.7.

The M-MCMA is a new protocol. Its theoretical foundation is straight forward, but in order to ensure that the protocol is effective, its foundation will be shown in the next part. The analysis of the success of the control is also shown there.

3.2. Theoretical foundation of the M-MCMA protocol

Originally, the number of the subtime slots k, which serve for the reservations in each reservation period, was chosen equal to three. That choice makes it possible that on average there was at least one successfully received reservation in each reservation period provided the average number of reservations in each of the subtime slots is equal to one. That can be seen in the following analysis:

If:

- N is the number of VBR's in the cell and N>>3;

- p_{per} is the probability that a VBR sends its reservation when it has a packet to transmit;

- α is the data packet arrival rate at each VBR,

then it can be assumed that:

on average $N/3$ VBR's will send their reservations with probability $\alpha . p_{per}$ in each of the subtime slots,

because:

each VBR chooses randomly a subtime slot in which it will send its reservation.

Thus the condition that an average number of reservations in each subtime slot is equal to one is equivalent to

$$N/3.\,\alpha . p_{per} = 1 \qquad or \qquad p_{des} = \alpha . p_{per} = 3/N \tag{5}$$

,where $p_{des} = 3/N$ is the desired probability with which each VBR will send its reservation in a reservation period. The actual probability that a VBR sends its reservation in a reservation period is $p_{act} = \alpha . p_{per}$. For the sake of simplicity, it is assumed in the analysis that the actual probabilities p_{act} are the same and equal to p for all of the VBR's.

If the independence of each other of the data arrival rates at the VBR's is assumed, the VBR's will send their reservations independently of each other. Thus the probability that the GBS has a successful reservation in each of the subtime slots is

$$P_{succ,1sts} = N/3.p.(1-p)^{N/3-1} \tag{6}$$

$P_{succ,1sts}$ can be considered as an average number of successful reservations that the GBS will have in each of the subtime slots. There are in total three subtime slots for reservations in each reservation period. Therefore, the average number of reservations that the GBS will have in each reservation period is

$$n_{3sts} = 3.P_{succ,1sts} = N.p.(1\text{-}p)^{N/3\text{-}1} \qquad (7)$$

If we can manage to have $p = p_{des} = 3/N$, the average number n_{3sts} for the cases when N is equal to 10, 20 and 30 will be equal to 1.30, 1.19 and 1.16 respectively.

The actual probability that each VBR will send its reservation in a free time slot is $p_{act} = \alpha .p_{per}$. Therefore, in order to make p_{act} be approximately equal to the desired value $p_{des} = 3/N$, an adaptive control is needed in order to change the probability p_{per} to suitable value according to the actual value of the average data arrival rate α at each VBR. In order to do that, a control code for setting the value of the probability p_{per} is transmitted to the VBR in the BRO-command. The GBS estimates the correct setting of the value of the probability p_{per} through the actual number of successful reservations that it will have in the reservation period. The probability p_{per} is set higher, for example, when all of the three subtime slots which serve for reservations were left empty and it is set lower, for example, when collisions occurred in all of the three subtime slots.

In principle, there must be two bounds of the successful control range:

- lower bound: when the average data arrival rate α at each VBR is too low. The value of the permission for reservation probability p_{per} can not be set higher than one. Thus the condition (5) can not be satisfied and the control is failed in this case;

- upper bound: when the average data arrival rate α is equal to one. This case causes no problems, because the value of p_{per} can be set as low as needed.

Thus there is only one bound for the success of the control. The control fails if the data arrival rate is lower than the lower bound α_{lb}, which depends on the number of VBR's in the cell. For example, the lower bound is equal to 0.3, 0.15 and 0.1 when the number of the VBR's N is equal to 10, 20 and 30 respectively. When the control fails, the permission probability p_{per} is equal to one, the actual probability p_{act} is equal to α and

$$P_{succ,1sts} = N/3.\ \alpha.(1-\alpha)^{N/3-1} \quad (8)$$

In this case, the M-MCMA protocol becomes a version of the reservation ALOHA (R-ALOHA) protocol.

It has been seen in the foregoing discussion that when $k=3$, the average number of successful reservations that the GBS will have in each reservation period is greater than one. Despite of this fact, the probability $P_{succ,tot}$ that the GBS has at least one successful reservation in each reservation period is only about 0.8. Thus a small buffer for ID-numbers is needed for the storage of the successfully received ID's. The calculated values of the success of control $P_{succ,tot}$ and the average number of successfully received reservations in each reservation period n_{aver} for four cases when N is equal to 10, 30, 60 and 120 are given in Table II. Those values are ideal values because the probability p was taken equal to the desired value $3/N$.

When the number of subslots for reservations k is equal to one, the M-MCMA becomes an 1-persistent version of the C-MCMA protocol in the region of low offered traffic, i.e. when the total offered traffic $G = \alpha .N < 1$. When $G > 1$, the throughput of the M-MCMA is maintained at the capacity level, while that of the C-MCMA is not.

4. M-MCMA FOR DATA TRANSMISSIONS ALONE

In this section, the case when the M-MCMA protocol is used for data transmissions alone is considered. When there is no voice traffic, there is no need for real time actions and a little delay will have no significant effects on the system performance. So the duration of the slot can be varied to improve the system performance. According to the analysis of Section 3, with the M-MCMA protocol there are three types of slots in up-link, namely normal, assigning and missing. If the following notations are used:

- eff_{norm} is the efficiency in using the normal slot for data transmission;
- eff_{ass} is the efficiency in using the assigning slot for data transmission;
- R is the channel transmission rate;
- a is the worst case propagation delay;
- t_{PROC} is the processing time before sending the acknowledgement;
- n_{BRO} is the length of the broadcast command in bits;
- n_{ASS} is the length of the assignment command in bits;
- n_{RES} is the length of a reservation packet in bits,

then from Figs. 4-6 we have

$$eff_{norm} = t_{Data} / t_{norm} \tag{9}$$

,where t_{Data} is the duration needed for sending the whole data packet and t_{norm} is the duration of the normal slot. If a data packet has a length of L bits, then

$$t_{Data} = L/R$$

and

$$t_{norm} = t_{Data} + t_{PROC} + 2.(k + 1).a + (k.n_{RES} + n_{BRO} + n_{ASS}) / R \qquad (10)$$

The missing slot has an efficiency of zero. In order to reduce the duration of an empty slot in the case when $k=1$, the missing slots are subdivided into the empty slots and the slots with collision. The durations of these two types of slots are

$$t_{emp} = 2.k.a + (n_{BRO} + k.n_{RES}.c) / R \qquad (11)$$

$$t_{coll} = 2.k.a + (n_{BRO} + k.n_{RES}) / R \qquad (12)$$

,where c is a factor which is equal to zero if $k=1$ and equal to one if $k>1$.

The efficiency in using an assigning slot is:

$$eff_{ass} = t_{Data} / t_{ass} \qquad (13)$$

,where t_{ass} is its duration

$$t_{ass} = t_{Data} + t_{PROC} + 2.a + n_{ASS} / R \qquad (14)$$

From the simulations, the numbers of the normal, assigning, empty slots and slots with collision n_{norm}, n_{ass}, n_{emp} and n_{coll} were obtained. Those numbers were used in the calculations of the throughput S of the system according to the following equation:

$$S = (n_{norm} \cdot t_{norm} + n_{ass} \cdot t_{ass}) / t_{sim} \tag{15}$$

, where t_{sim} is the simulation duration

$$t_{sim} = n_{norm} \cdot t_{norm} + n_{ass} \cdot t_{ass} + n_{emp} \cdot t_{emp} + n_{coll} \cdot t_{coll} \tag{16}$$

The expected performance of the M-MCMA protocol can be easily seen through calculations. In the general case when the number of subslots for reservations is k, if the desired control is achieved, the probability that the GBS will have at least one successful reservation in each reservation period is

$$P_{succ} = \sum_{l=1}^{k} \binom{k}{l} . P_{succ,1sts}{}^{l} \cdot \left(1 - P_{succ,1sts}\right)^{k-l} \tag{17}$$

and the average number of successful reservations in each reservations period with k subslots is

$$n_{aver} = \sum_{l=1}^{k} \binom{k}{l} . l . P_{succ,1sts}{}^{l} \cdot \left(1 - P_{succ,1sts}\right)^{k-l} \tag{18}$$

If the radio channel is assumed to be perfect and the throughput is defined as the fraction of time used for transmissions of the whole data packets including the header and other control fields, then the expected throughput of the M-MCMA protocol can be calculated by the following equation:

$$S=\frac{(per_{norm}+per_{ass}).t_{Data}}{per_{norm}.t_{norm}+per_{ass}.t_{ass}+per_{emp}.t_{emp}+per_{coll}.t_{coll}} \quad (19)$$

,where

- per_{norm} is the percentage of the normal slots;
- per_{ass} is the percentage of the assigning slots;
- per_{emp} is the percentage of the empty slots;
- per_{coll} is the percentage of the slots with collision;
- t_{norm} is the duration of a normal slot;
- t_{ass} is the duration of an assigning slot;
- t_{emp} is the duration of an empty slot.
- t_{coll} is the duration of a slot with collision.

The percentage of the normal slots and assigning slots can be calculated through the equations:

$$per_{norm}=\frac{P_{succ}}{n_{aver}+1-P_{succ}} \quad (20)$$

$$per_{ass}=\frac{n_{aver}-P_{succ}}{n_{aver}+1-P_{succ}} \tag{21}$$

The percentage of the empty slots and slots with collision can be calculated through the equations:

$$per_{emp}=\frac{P_{emp}}{n_{aver}+1-P_{succ}} \tag{22}$$

$$per_{coll}=(1-per_{norm}-per_{ass}-per_{emp}) \tag{23}$$

,where

$$P_{emp} = (1-p)^N \tag{24}$$

Table III shows the calculated values of the percentage of the normal slots per_{norm} and the percentage of the assigning slots per_{ass} for four cases when the number of subslots for reservations k has a value from 1 to 4.

When the lengths of the BRO and ASS packets are 32 bits, that of the RES packet is 24 bits and the processing time before sending the acknowledgement is neglected, the expected throughput of the M-MCMA protocol can be up to 85% for the case when there are three subslots for reservations in each reservation period. The calculated throughput of the M-MCMA protocol for different values of the number of subslots for reservations k is shown in Table IV. In this table, R is the channel rate and a is the worst case propagation delay.

5. SIMULATION RESULTS

This section shows the simulation results of the Modified Minipacket Competition Multiple Access protocol (M-MCMA) when it is used for data transmissions alone and the radio channel is assumed to be perfect. Simulations have been done for different cases when the channel rate R is equal to 1 Mbps and 2.5 Mbps with the worst case propagation delay a in the cell is equal to 6, 10 and 25 microseconds. Other parameter values that were used in the simulations are:

- the number of the user stations (VBR's) is 10, 30, 60 and 120;
- the average length of data packets L is 1000 bits;
- the number of the control bits is 6;
- the BRO-command has the length of n_{BRO}= 32 bits;
- the ASS-command has the length of n_{ASS}= 32 bits;
- the reservation RES has the length of n_{RES}= 24 bits;
- the VBR's have no buffers for data packet;
- the data arrival rate α at each VBR changes from 0 to 1 packet/slot with the step size of 0.01 or from 0 to 0.2 with the step size of 0.002;
- the duration of the simulation process for each value of the data arrival rate α is 800 or 8000 slots ;
- the processing time t_{PROC} before sending an acknowledgement ACK is neglected;
- there is no down link traffic.

Simulations have been done with the assumption that the arrival of packets has a geometric distribution. For the sake of simplicity, the data arrival rate is assumed to be independent of the type of the slots. The simulation process is shown in Fig.8. The value of the throughput in the simulation results is calculated by equation (15).

Fig.9 shows the simulation results of the case when k is three, R is 1 Mbps and a is 6 μs with the number of users is 10, 30, 60 and 120. It can be seen from that figure that when the offered traffic is high enough, the throughput of the M-MCMA is nearly independent of the number of data users and it is maintained at the capacity level despite how heavier the offered traffic becomes. The simulation results of the M-MCMA protocol with different values of the number of subslots for reservations k is shown in Fig.10. The number of the VBR's was taken equal to 60 and the maximum data arrival rate at each VBR is 0.1. The worst case propagation delay and the channel rate of Fig.10 are the same as those of Fig.9. In Fig.10, the falling line shows the calculated data throughput when k is one and there is no control. Other lines show the throughput when k changes from 1 to 4 and the control is used. It can be seen from this figure that when the M-MCMA protocol is used for data communication alone, the value of one of the number of subslots k may be preferred.

Results of the simulations of the M-MCMA protocol for different cases when the number of subslots for reservations k has a value from 1 to 4 are given in Table V. Those values are the average ones obtained by averaging the simulation results over 15 consecutive instantaneous values in the region of high offered traffic. A comparison of the results in Table IV with those in Table V proves the effectiveness of the control mechanism of the M-MCMA protocol and the usefulness of the equations for calculations of the expected throughput (17)-(24). The data throughput is about 0.85 in the case when channel transmission rate $R = 1$ Mbps and worst case propagation delay $a = 6\ \mu s$. It decreases to about 0.63 when $R = 2.5$ Mbps and $a = 25\ \mu s$. These simulation results show that the M-MCMA protocol can be very effective when it is used in a micro-cell or pico-cell.

The calculation and simulation results of both M-MCMA and improved C-MCMA protocols are shown in Table VI. From this Table, it can be seen that when the number of subslots is three, the throughput of the M-MCMA protocol is only about 1% lower than the capacity of the improved version of the C-MCMA protocol. The throughput can be made a little higher by taking a greater k (conf. Table IV & V). From the calculated and simulation throughput we can see that the M-MCMA is a very attractive protocol, specially when the demand traffic is high or largely varied.

At low traffic, when $G = \alpha .N < 1$ the percentage of the normal slots of the M-MCMA protocol with $k = 1$ is the same as that of the 1-persistent C-MCMA protocol. The difference of about 4% of the throughput of the protocols in that case is partly due to the fact that the length of the BRO and ASS commands of the M-MCMA is taken longer than that of the TRY and STOP commands of the C-MCMA. The main reason for that difference is the manner of consideration and calculations. With the C-MCMA, the minipacket used as a reservation packet is considered as the beginning part of the data packet, while the RES packet of the M-MCMA is not.

6. CONCLUSIONS:

In this paper, a new protocol with the name Modified Minipacket Competition Multiple Access (M-MCMA) has been described. The case when the protocol is used for data communications alone is considered with different number of subslots for reservations *k*. Simulation results showed that the M-MCMA is a very attractive protocol. When the offered traffic is high enough, the data throughput is maintained at the capacity level, despite how heavier the traffic becomes. The data throughput can be up to about 85% in the case when *k* is three. Moreover, the offered traffic can be very easily estimated. Based on this ability of the M-MCMA protocol, the Dynamic Channel Allocation of the cellular system can be supported very effectively. So the new concept "intelligent cellular system" can be developed in which the system capacity is flexibly adapted to the demand traffic and the ability of the fixed network at that moment. The frequency planning will be then no longer a big problem.

At low traffic, the M-MCMA becomes the R-ALOHA with the *k* subslots for reservations in each reservation period. In this case, if *k* is equal to one, the M-MCMA becomes the 1-persistent C-MCMA protocol. The great advantage of the M-MCMA protocol is that the throughput can be maintained at the capacity level when the offered traffic is higher than that what improves the system performance in the environment where the offered traffic is largely varied.

Although the exact analysis of the M-MCMA protocol for the case when the offered traffic is higher than the capacity may not to be carried out, the expected performance of the protocol can be very easily calculated. The calculation results match those of simulations very nicely. The number of subslots k in each reservations period was chosen equal to three, but it can be taken equal to an arbitrary positive integer number. The higher the value of k, the higher capacity is expected, but the throughput will be a little lower when the offered traffic is less than the capacity. When the M-MCMA protocol is used for data communication alone, the value of one of the number of subslots for reservations k may be preferred. But when the slot duration is fixed, other values of k may have their advantages.

M-MCMA can be combined with other protocols such as Circuit Reservation Multiple Access (CRMA) [5,6] or Packet Reservation Multiple Access (PRMA) and its versions [7-9] to form the hybrid ones for mixed voice /data radio communications. Although the M-MCMA is more complex than other well-known protocols, its implementation in both hardware and software is expected to be not too difficult or expensive.

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Captions of figures:

Fig.1. Timings of a minislot with collision and of an idle minislot of the original C-MCMA protocol.

Fig.2. Timing of a slot with successful transmission of the original C-MCMA protocol.

Fig.3: Calculated throughput of the original and improved versions of the C-MCMA protocol for the case when the normalized propagation delay $a = 0.006$, normalized minipacket length $w = 0.025$ and the data packet length is 1000 bits.

Fig.4. Timing of a missing slot of the M-MCMA protocol.

Fig.5. Timing of a normal slot of the M-MCMA protocol.

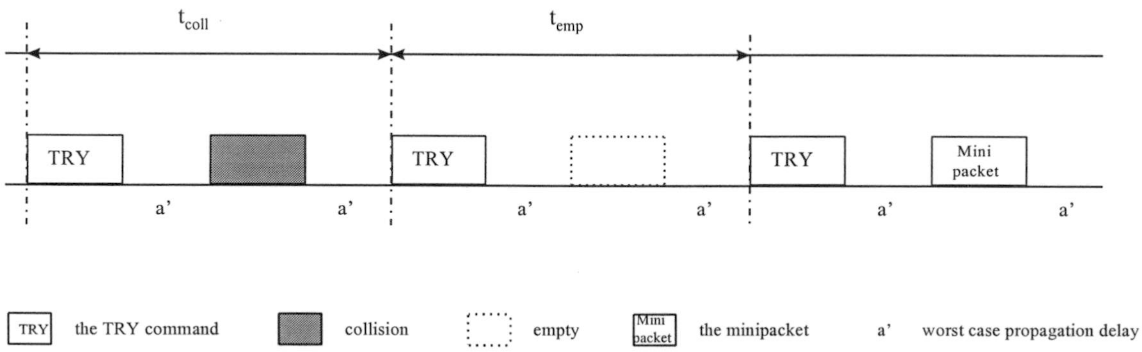
Fig.6. Timing of an assigning slot of the M-MCMA protocol.

Fig.7. The main parts of the assignment command ASS, broadcast command BRO and reservation packet RES of the M-MCMA protocol.

Fig.8. Simulation process for each value of the data arrival rate α at each VBR when the M-MCMA protocol is used for data communications alone.

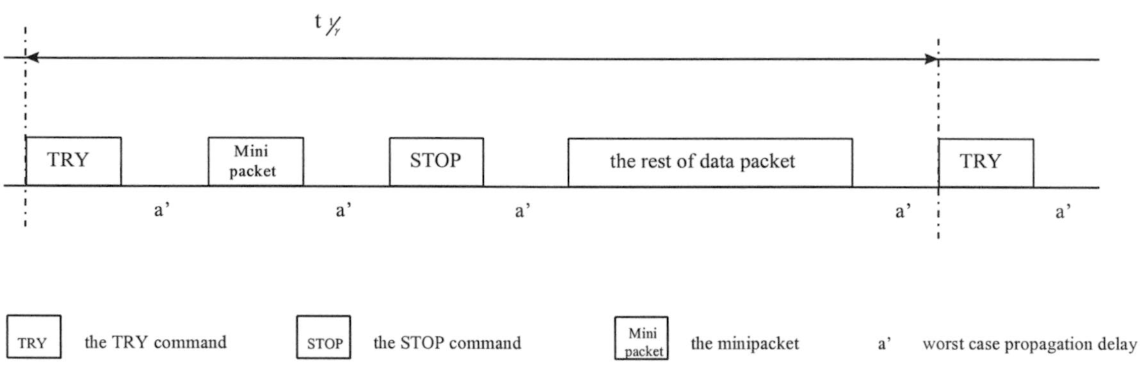
Fig.9. Throughput of the M-MCMA protocol with different numbers of data users n_vbr when the number of subslots for reservations k in each reservation period is 3.

Fig.10. Throughput of the M-MCMA protocol with different numbers of subslots for reservations k when the number of users is 30.



t_{coll}
t_{emp}
TRY
TRY
TRY
Mini packet
a'
a'
a'
a'
a'
a'
TRY
the TRY command
collision
empty
Mini packet
the minipacket
a'
worst case propagation delay

Fig.1.



$t_{1/\gamma}$
TRY
Mini packet
STOP
the rest of data packet
TRY
a'
a'
a'
a'
a'
TRY
the TRY command
STOP
the STOP command
Mini packet
the minipacket
a'
worst case propagation delay

Fig.2.

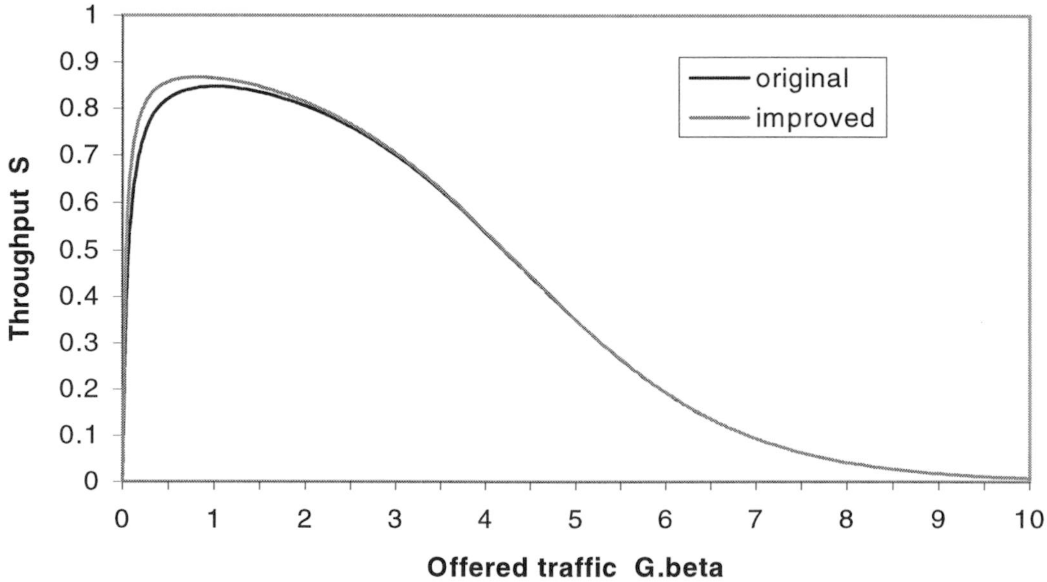

Throughput S
Offered traffic G.beta
original
improved
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
1
2
3
4
5
6
7
8
9
10

Fig.3:

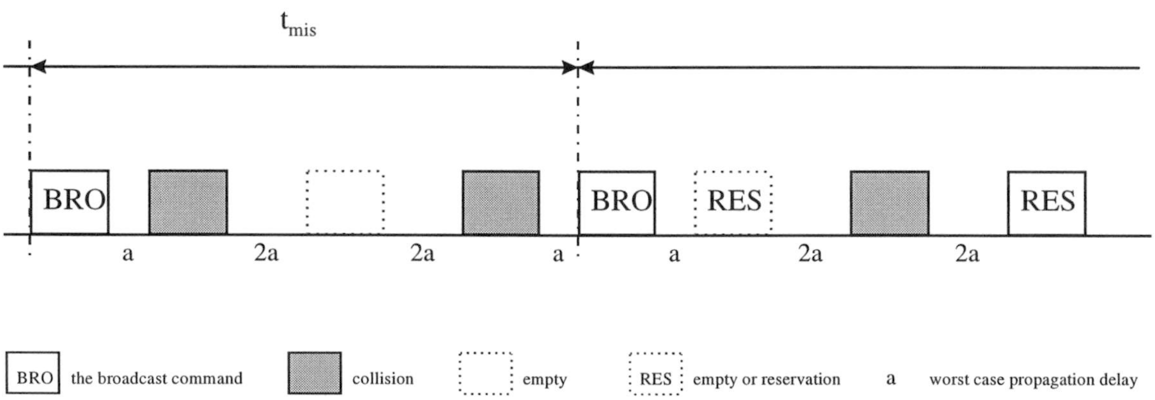

t_{mis}
BRO
BRO
RES
RES
a
2a
2a
a
a
2a
2a
BRO the broadcast command
collision
empty
RES empty or reservation
a worst case propagation delay

Fig.4.

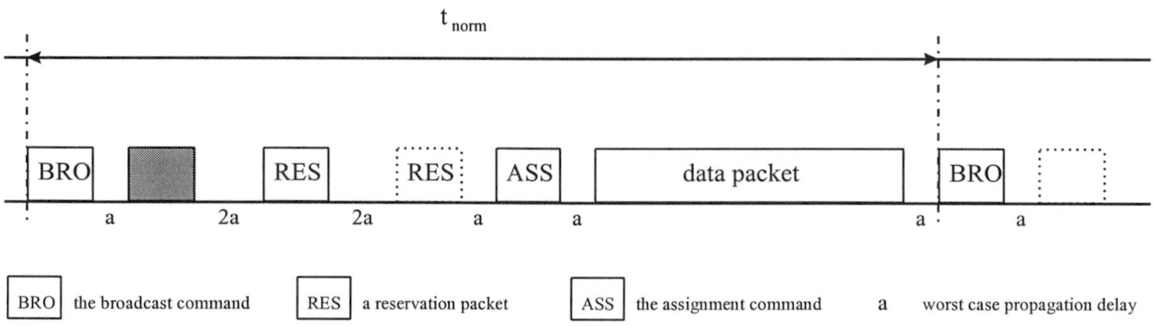

t norm
BRO
RES
RES
ASS
data packet
BRO
a
2a
2a
a
a
a
a
BRO the broadcast command
RES a reservation packet
ASS the assignment command
a worst case propagation delay

Fig.5.

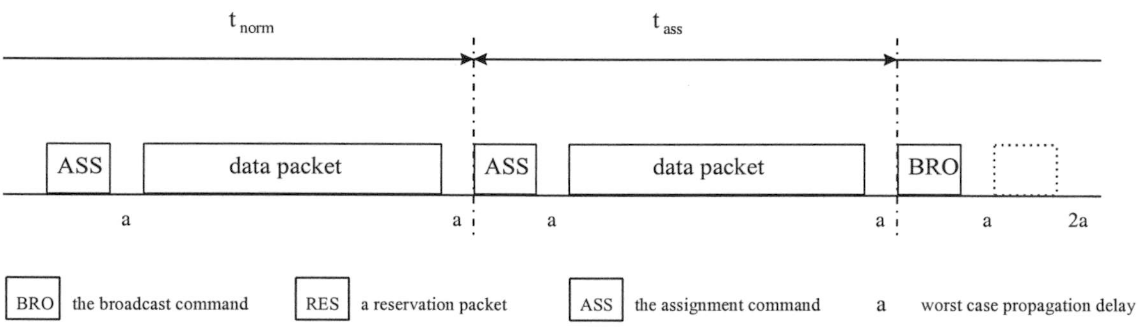
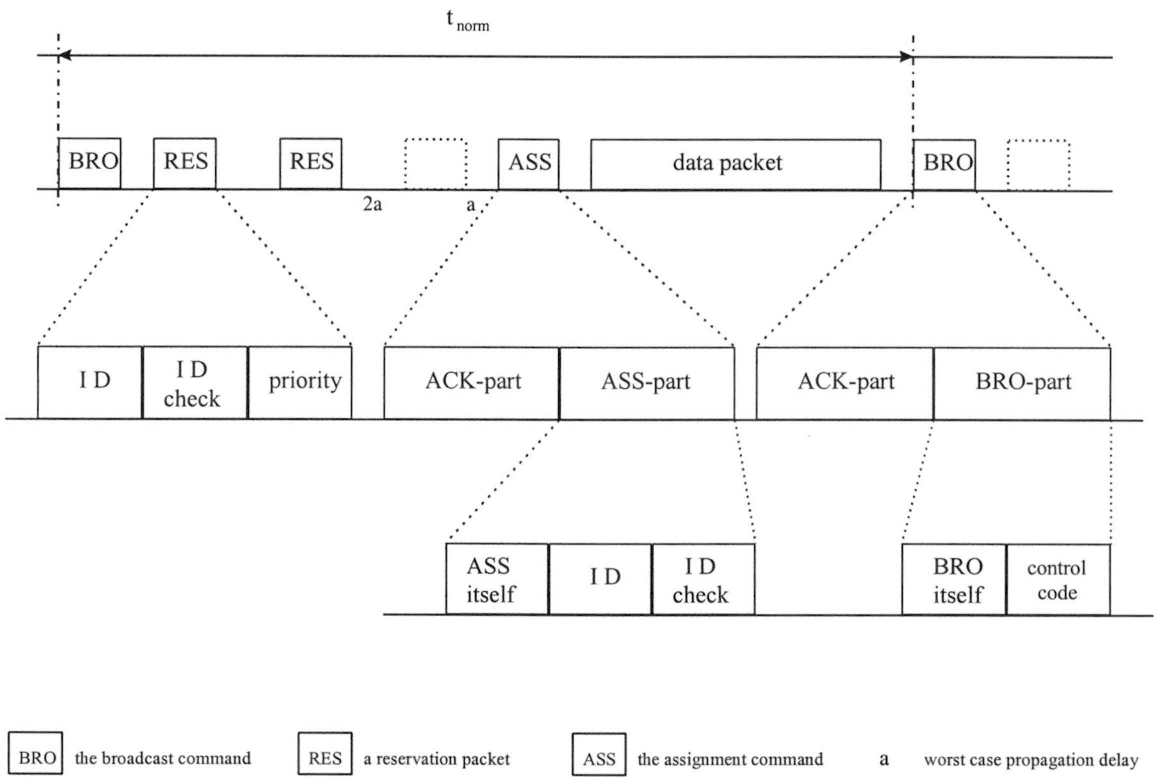

t norm
t ass
ASS
data packet
ASS
data packet
BRO
a
a
a
a
a
2a
BRO the broadcast command
RES a reservation packet
ASS the assignment command
a worst case propagation delay

Fig.6.



t norm
BRO
RES
RES
ASS
data packet
BRO
2a
a
ID
ID check
priority
ACK-part
ASS-part
ACK-part
BRO-part
ASS itself
ID
ID check
BRO itself
control code
BRO the broadcast command
RES a reservation packet
ASS the assignment command
a worst case propagation delay

Fig.7.

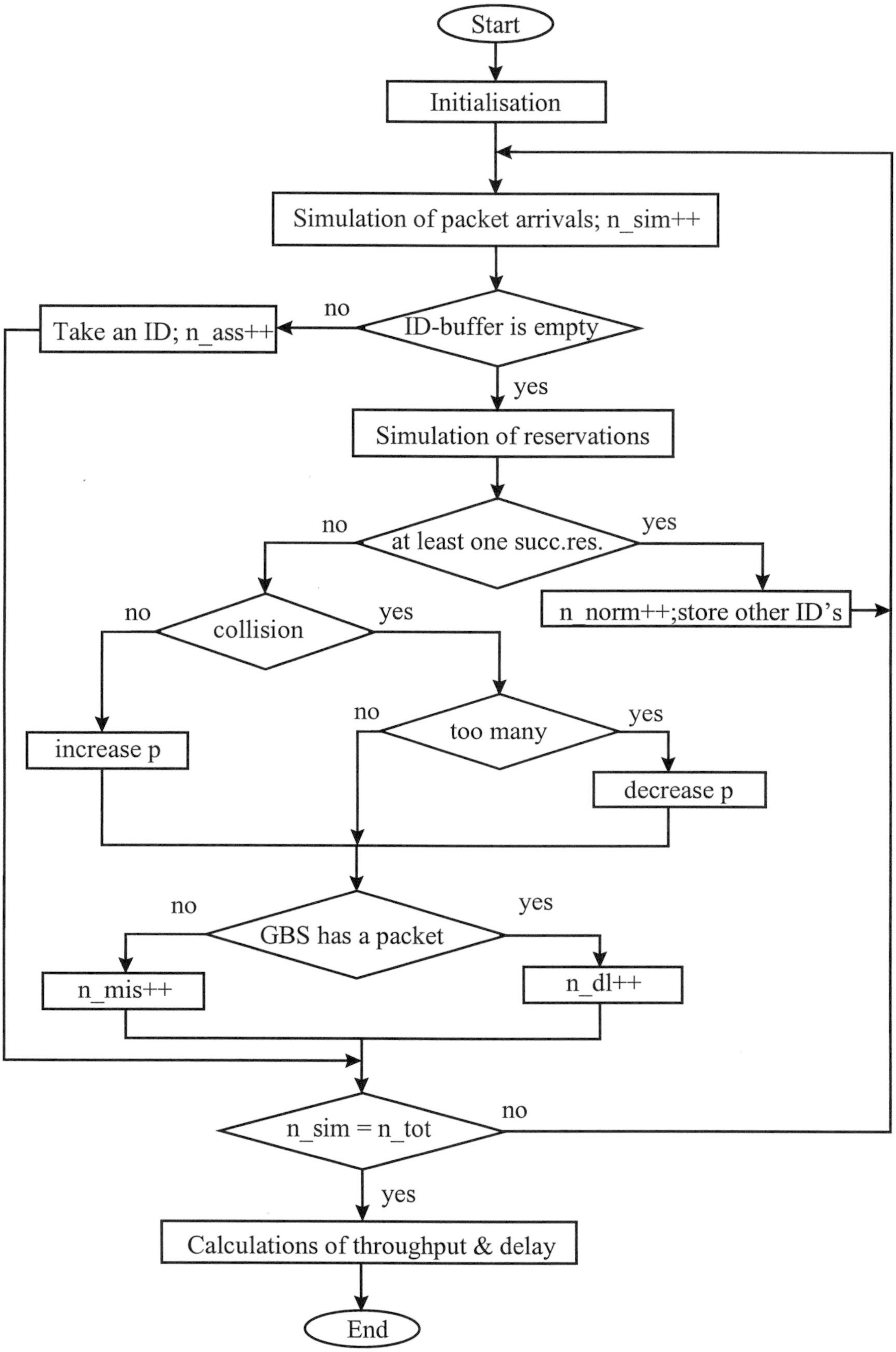

Start
Initialisation
Simulation of packet arrivals; n_sim++
ID-buffer is empty
no
Take an ID; n_ass++
yes
Simulation of reservations
at least one succ.res.
no
yes
n_norm++;store other ID's
collision
no
yes
increase p
too many
no
yes
decrease p
GBS has a packet
no
yes
n_mis++
n_dl++
n_sim = n_tot
no
yes
Calculations of throughput & delay
End

Fig.8.

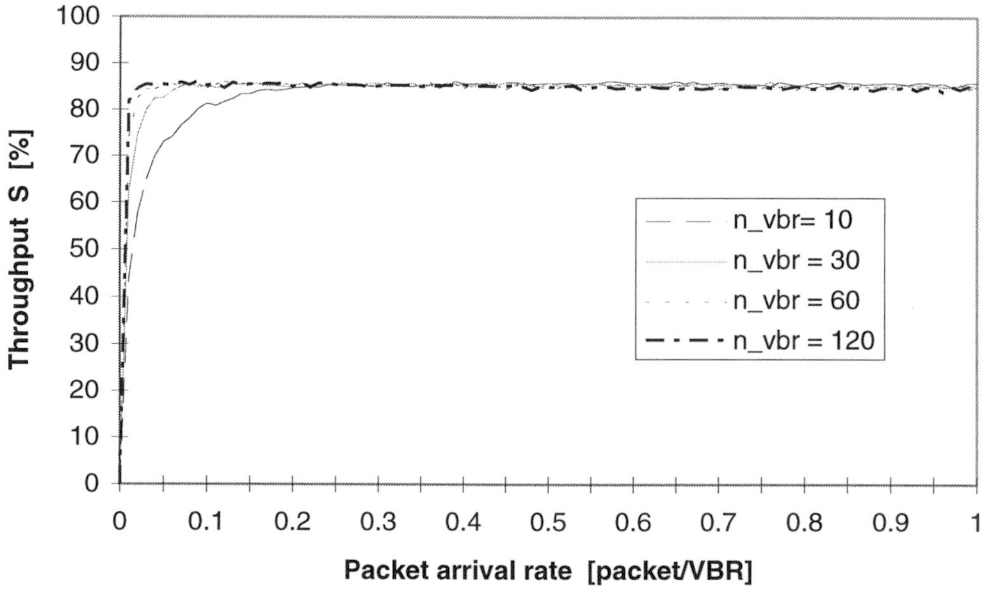

100
90
80
70
60
50
40
30
20
10
0
Throughput S [%]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Packet arrival rate [packet/VBR]
n_vbr= 10
n_vbr = 30
n_vbr = 60
n_vbr = 120

Fig.9.

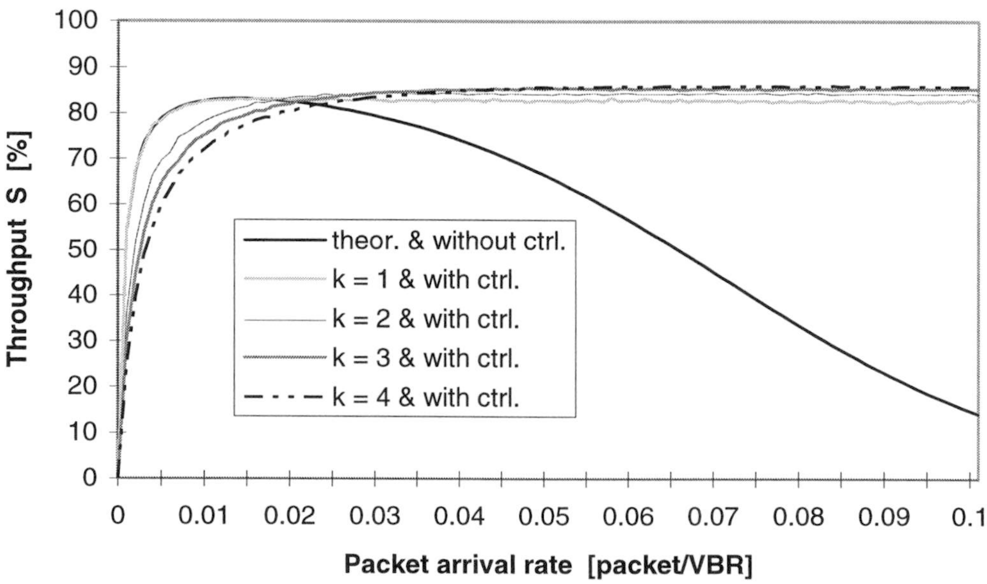

100
90
80
70
60
50
40
30
20
10
0
Throughput S [%]
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Packet arrival rate [packet/VBR]
theor. & without ctrl.
k = 1 & with ctrl.
k = 2 & with ctrl.
k = 3 & with ctrl.
k = 4 & with ctrl.

Fig.10.

Captions of tables:

TABLE I
Calculated capacity of the original and improved versions of the C-MCMA protocol when the number of VBR's is 60 and the packet arrival has a geometric distribution.

TABLE II
Calculated average numbers of successful reservations n_{aver} and the success control probabilities $P_{succ,tot}$ of the M-MCMA protocol when k is 3.

TABLE III
Calculated values of the percentages of the normal and assigning slots of the M-MCMA protocol with different values of subslots for reservations k when the number of VBR's is 60.

TABLE IV
Calculated throughput of the M-MCMA protocol when it is used for data transmission alone and the number of VBR's is 60.

TABLE V
Simulation results of the throughput of the M-MCMA protocol when it is used for data transmission alone and the number of VBR's is 60.

TABLE VI
Comparisons of the simulation results with the calculated throughput of the M-MCMA protocol when it is used for data transmission alone. The number of VBR's is 60 and k=3. Comparison of the throughput of the M-MCMA protocol with the capacity of the improved version of the C-MCMA protocol.

TABLE I

a [μs]	R [Mbps]	C	$C_{improved}$
6	1	0.847	0.865
	2.5	0.802	0.818
10	1	0.826	0.844
	2.5	0.757	0.771
25	1	0.757	0.771
	2.5	0.625	0.635

TABLE II

N	$P_{mis,tot}$	$P_{succ,tot}$	n_{aver}
10	0.180	0.820	1.31
30	0.230	0.770	1.16
60	0.241	0.759	1.13
120	0.247	0.753	1.12

TABLE III

	k = 1	k = 2	k = 3	k = 4
P_{succ}	0.371	0.608	0.759	0.853
n_{aver}	0.371	0.748	1.132	1.523
per_{norm}	0.371	0.534	0.552	0.511
per_{ass}	0	0.123	0.272	0.401

TABLE IV

a [μs]	R [Mbps]	k = 1	k = 2	k = 3	k = 4
6	1	0.831	0.845	0.856	0.862
	2.5	0.787	0.801	0.811	0.816
10	1	0.811	0.825	0.836	0.841
	2.5	0.744	0.756	0.765	0.771
25	1	0.744	0.756	0.765	0.771
	2.5	0.617	0.626	0.633	0.637

TABLE V

a [μs]	R [Mbps]	k = 1	k = 2	k = 3	k = 4
6	1	0.827	0.843	0.854	0.859
	2.5	0.784	0.798	0.807	0.813
10	1	0.807	0.822	0.832	0.837
	2.5	0.740	0.753	0.761	0.765
25	1	0.740	0.754	0.761	0.766
	2.5	0.614	0.622	0.627	0.630

TABLE VI

a [μs]	R [Mbps]	M-MCMA calculated	M-MCMA simulated	C-MCMA calculated	C-MCMA simulated
6	1.0	0.856	0.854	0.868	0.865
	2.5	0.811	0.807	0.821	0.818
10	1.0	0.836	0.832	0.847	0.844
	2.5	0.765	0.761	0.774	0.771
25	1.0	0.765	0.761	0.772	0.771
	2.5	0.633	0.627	0.638	0.635