Performance Analysis of the Delay-Tolerant Satellite Distributed MAC Reservation Protocols

Alexander Markhasin
Department of Telecommunication Networks
Siberian Telecommunications University (SibSUTIS)
Novosibirsk, Russia
almar@rinet.su

Abstract—The key challenges of the QoS-oriented satellite MAC technology are conditioned mainly by long-delay space medium. They represent phenomena of MAC’s performance degradation (“time barrier”) and dynamical instability (“dynamic barrier”) which appear when the propagation time increases. The delay-tolerant MACs should guarantee an effective overcoming of both barriers. We showed that the delay-tolerant abilities depend on the processing algorithm of MAC commands. The serial processing algorithm of the MAC commands (SCP) is characterized as delay-intolerant. The parallel commands' processing algorithm (PCP) provides the time tolerance, i.e., effective overcoming of the time barrier, mainly. The CCP algorithm is used by the MAC reservation protocols with fixed, or pre-defined, superframe formats (RFS). The parallel-conveyor commands' processing algorithm (CCP) guarantees the full delay tolerance abilities. The CCP algorithm is used by MAC reservation protocols with adaptive frames formats (RAF), which adjust to a current data flows. This paper presents the numeric-analytical method and performance analysis of the delay-tolerant and fully mesh, i.e., multipoint-to-multipoint (MPMP) mode, satellite MAC reservation protocols with distributed dynamic control of the quality of services (QoS). The comparative analysis of the named above MAC reservation schemas is also given.

Keywords—delay-tolerant, MAC, reservation, QoS, mobile, satellite, mesh, dynamic control, analysis, optimization, multidimensional queueing, time barrier, dynamic barrier.

I. INTRODUCTION

The distributed multiple access control to long-delay space medium (MAC) with dynamic (i.e., "on-the-fly") control of bandwidth resources, traffic parameters, quality of services (QoS), and also of the distributed priority queues is a key networking technology for 4G mobile satellite communications [1, 2]. The fundamental features of satellite MAC are the principle incompleteness and large delays of the MAC’s real-time status information. This information is necessary to meet strong requirements to the distributed dynamic control of the 4G mobile satellite communications. Indeed, this real-time status information is dispersed on space distributed stations, and therefore it is inaccessible for the "MAC collective intellect" up to its transmission and propagation in the common long-delay space medium [3]. It gives birth to fundamental barriers problem. As shown in [1, 4], the time barrier becomes apparent by the effect of degradation of the long-delay MAC throughput capacity when the propagation time increases many times. The dynamic barrier arises for such essential reason as principle dynamic instability of the mechanism of adaptation of the superframes’ useful capacity of the reservation MAC with fixed, i.e., pre-defined, superframe formats (RFS) to the varying traffic intensity, observed in the long-delay mediums [4].

This paper focuses on the analysis of the delay-tolerant and fully mesh on the MAC sublayer, i.e., multipoint-to-multipoint (MPMP) mode, satellite MAC reservation protocols with distributed dynamic (“on-the-fly”) control of the QoS and bandwidth resources (see [2]). Such satellite MAC protocols are described by distributed multidimensional priority queuing systems [5]. Mobile WiMAX systems which operate in the point-to-multipoint (PMP) mode and the short-delay medium are also described by this model [6]. Unfortunately, such distributed multidimensional queuing models does not have a strict analytical solution in the realistic problem statement that takes in account the real conditions of a MAC operational environment [5]. A few analytical models have been presented in literature to analyze the WiMAX-like MAC performance [6-11]. However, it was possible to find the analytical results only under strong simplifying assumptions: one-dimensional infinite queues without priority, excluding errors, homogeneous traffic, static QoS control, short-delay medium (i.e., small round-trip-time), PMP mode, etc. Therefore, the simulation is used to estimate the adequate MAC characteristics in real conditions of the wireless environment [6, 12]. To eliminate the simplifying assumptions mentioned above and investigate the delay-tolerant MAC performance in real conditions of a satellite operational environment, we developed a numeric-analytical method of balance of the load intensity [5, 13]. Finally, the results of numerical researches, including performance comparison of the fixed (RFS) and adaptive (RAS) MAC reservation protocols, are presented.

II. THE LONG-DELAY MAC RELEVANT TECHNIQUES

Now, we define the MAC delay tolerance as its ability to overcome the time and dynamic barriers [1]. The delay-tolerant MAC protocols should guarantee an effective overcome of both barriers. In [1, 14], we have shown that the MAC’s delay time tolerance ability depends on the algorithm of MAC commands processing The serial algorithm of commands processing (SCP, Fig. 1a) was characterized as delay-intolerant. The parallel algorithm of commands processing (PCP, Fig. 1,b) ensures the time-tolerance, i.e., effective overcoming of the time barrier, mainly. The PCP algorithms are used by the MAC reservation protocols with fixed, or pre-defined, superframe formats (RFS) [15, 16]. The conveyor-parallel algorithm of commands processing (CCP, Fig.1,c) guarantees a full delay tolerance. The CCP algorithm

978-1-4244-3559-3/09/$25.00 ©2009 IEEE

IWSSC 2009
is provided by the MAC reservation protocols with adaptive frame formats (RAS) [1, 2].

The time diagram of MPMP modes satellite MAC command processing is shown in Fig. 1. The satellite plays the role of a virtual bridge (VB) or retransmitter (RS). Together with a full set of the distributed mobile earth stations (MS) the satellite establishes the multi-access up channel and the broadcast down channel that operate in the MPMP mode, i.e., all MSs receive via down broadcast channel the same packet flow transmitted via up multi-access channel from each MSs within given MAC covering. The MPMP is a preferable operating mode of mobile satellite MAC because it provides very important advantages including:

- minimum number of hops, or single-hop connectivity,
- fully distributed MAC and dynamical control of QoS [2],
- fully mesh MSs topology, i.e., each-to-each, alternatively WiMAX PMP mode possible MSs connections like neighbour-to-neighbour,
- low-cost full distributed, or grid-like, satellite networks architecture [2],
- easy on-board satellite equipment.

III. THE MODELS OF THE DELAY TOLERANCE MAC ABILITIES

As it’s shown in Fig. 1a, all adjacent MAC transactions are separated via round-trip-time pauses by serial SCP algorithm. Therefore SCP MAC protocol throughput capacity can be expressed following [1, 3] as

\[ C_{SCP} = \frac{\Delta}{1 + v_{MAC} + v_{RTD}} , \]

where \( v_{MAC} \) is the time overhead \( \tau_{c} \) on the distributed MAC normalized by mean/deterministic packet duration \( M[\tau] \),

\[ v_{MAC} = \tau_{c} / M[\tau] , \]

\( v_{RTD} \) is the round-trip-time \( T_{RTD} \) normalized overhead,

\[ v_{RTD} = T_{RTD} / M[\tau] . \]

In line with (1)-(3), the serial processing MAC throughput capacity will decrease up to zero by increasing of the RTD

\[ \lim_{T_{RTD} \rightarrow \infty} C_{SCP} = 0 . \]

Therefore the serial processing MAC performance will be degraded quickly when RTD increase (see Fig. 2). Hence, serial SCP MAC mode should be characterized as delay-intolerant.

As it is shown in Fig. 1b, the parallel commands’ processing technique PCP MACs operate on the fixed, or pre-defined, superframe formats (RFS) basis excluding the RTD pauses between the adjacent MAC transactions of the differ MSs. On the contrary, the adjacent MAC transactions of the same MS should be separated over time intervals to satisfy the condition

\[ \Delta T \geq T_{RTD} . \]

The superframe includes two fields: the control subframe (CS) formed by some number \( N \) of request/reservation mini-slots, and the data subframe (DS) formed by some number \( J \) of data slots. To satisfy the condition (5), the DS-reservations’ superframe should be shifted relative to the same MS’ CS-requests’ superframe on the some integer \( d \) superframes, where \( d = \lfloor \frac{I(T_{RTD}/T_{RFS})}{1} \rfloor \) is an integer part from the \( x \).

At last, to reduce the packets delay it is expedient to use the
sliding window mechanism. As in Fig. 1b, the size of the sliding windows is equal to
\[ m = 2d + 1 = 2I(T_{RTD} / T_{RFS}) + 3. \] (6)

Thanks to above parallel techniques, the PCP MAC allows to exclude the useless bandwidth resource overheads on RTD and to overcome the time barrier (see Fig. 2). In this case the RTD plays a role of transport delay. Hence, the PCP MAC can be characterized as time-tolerant.

However, a critical PCP MAC difficulty is an adaptation of the pre-defined superframes format, or RFS useful capacity
\[ C_{PCP, RFS} = 1/(1 + 2\Delta) \] (7)
to the upload traffics’ varying intensity \[ J \], where \( N \) and \( J \) are the numbers of the control (CS) and data (DS) slots, \( v_{MAC} \) is the normalized overhead (2). In line with (5) and Fig. 1b, the current requested DS number \( J \) is available after the CS transmission in long-delay wireless medium, but necessary for pre-defining the current RFSs format before this transmission [3]. Therefore the number of the requested slots for data packets, on the one hand, and number of the current RFS’ data slots \( J \), on the other hand, are not coincide, in principle. Really, or DS redundancy, or DS overflow (lack of slots) occurs.

The above mismatch leads to decrease of the PCP MAC throughput capacity \( C_{PCP, MAC} \) relatively of RFS useful utilizing (7). Following [1, 3] and (7), we can derive the expression for PCP MAC throughput capacity as
\[ C_{PCP, MAC} = 1/(1 + b_j N \Delta v_{MAC}), \] (8)
where \( b_j \) is the factor depending on the optimality of the dynamic adaptation of current value \( J \), or RFS useful capacity (7), to current upload traffic intensity. Clearly, \( b_j = 1 \) if all date slots DS will be permanently busy, and \( b_j > 1 \), otherwise. Clearly also, that the equality \( b_j = 1 \) can be achieved only asymptotically for infinite request queues when the utilization factor \( \rho \rightarrow 1 \).

As shown in [4], the packets delay becomes more and more critical with respect to the adaptation of the pre-defined RFS’ useful capacity to the current traffic. Thus, the packet delays can be increased similar to the avalanche when the input traffic intensity increases dynamically while poor adaptation of the current superframe format. Hence, the PCP can’t guarantee the MAC dynamic control stability, in principle, and can be characterized as dynamic-intolerant.

The conveyor-parallel commands’ processing CCP algorithm operates also without pauses (see Fig. 1c) on the basis MAC reservation protocols with \( M \)-periodical adaptive superframe (RAS) epoch, where epoch period \( M \gg N_{MS} \), \( N_{MS} \) is MSs quantity. Each RAS epoch includes \( M \) adaptive frame intervals \( \{t_j, j\in M-1\} \) marked by frames’ physical MAC-address identifiers’ \( j, j=0, 1, ..., M-1 \). In one’s turn, each \( j \)-th frame interval contains one mandatory CS mini-slot for \( j \)-th MS request’s, and one optional DS slot which was reserved/permitted for \( (j - z) \)-th MS data packet’s, where \( z \) is some variable integer \( z \) which satisfy the condition like (5)
\[ \Delta T=t_j - t_{j-z mod(M)} \geq T_{RTD}, j, z \in \{0, 1, ..., M-1\}. \] (9)

Thus, the RAS superframe epoch will be adapted dynamically (“on-the-fly”) to current data packets’ flow, without any RTD pauses between the adjacent transactions, any DS redundancy, and any DS overflows’. Hence, the CCP MAC throughput capacity can be calculated as [3, 4]
\[ C_{CCP} = 1/(1 + v_{MAC}). \] (10)

The CCP MAC technique applies effectively in the RS-token broadcast reservation (TBR-RS) MAC protocol [4]. This protocol uses the remarkable properties of the recurrent M-sequences (RS) in order to design a RS-token tools “all-by-one” for high effective multiple access to long-delay space medium, “on-the-fly” driving of the fully adapted RAS superframe RS-epoch, soft QoS provision and distributed dynamical control of traffic parameters, and bandwidth resources [2]. The \( M \)-subsequences \( A_j = a_j, a_{j+1}, ..., a_{j+M-1} \) serve as \( j \)-th MS’ physical MAC-address identifiers, \( j \in \{0, 1, ..., M-1\} \), \( n = 64 + 128 \). Every \( j \)-th RS-token MAC address can be cumulatively identified using one unique RS-address bit \( a_j \) per one \( j \)-th requests’ control mini-slots’ CS. Some subset \( \{a_j, k = 1, 2, ..., m_j\} \) of the \( i \)-th MS’ "personal" identifiers play the role of a tool for bandwidth resource optimal allocation in proportion to the \( i \)-th subset power \( m_j \). The required bandwidth resource \( Y_{ii} \) can be dynamically (“on-the-fly”) optimally assigned to each \( i \)-th MSs on a decentralized basis using Shannon-Fano coding method.

In line with results obtained in [3]-[5], the above CCP MAC technique "all-by-one" tools guarantee an effective overcoming of both time and dynamic delay-relevant barriers. Therefore, the CCP MAC reservation protocols’ with adaptive superframes’ (RAS) can be characterized as fully delay-tolerant.

IV. ANALYSIS OF THE RESERVATION RAF MAC PROBLEM

Now let us consider the analysis problem of the QoS-oriented distributed satellite PCP MAC reservation MPMP mode protocol with fixed superframes (RFS). As above, such satellite MAC protocols are described by distributed multidimensional priority queueing systems. Unfortunately, there is no strict analytical solution for such systems in the realistic problem statement that takes in account the real conditions of a MAC operational environment. In [4, 5], the numeric-analytical solution of the analysis and optimization problem of multiservices CCP MAC broadcast reservation protocols with adaptive superframes (RAS) was obtained. In this Section, we develop a numeric-analytical method of balance of the traffic intensity [5, 13] for PCP MAC reservation protocol with fixed superframes (RFS).

The main idea of this method is a decomposition of the model of the common multidimensional distributed \( M/G/m/n \) kind queue on an equivalent sum of linearly independent, or partial one-dimensional queues
\( M / M_k / m / n_{ik} \) finding the equivalent laws \( \tilde{M}_{ik} \) of the service time distribution in \( i \)-th partial queues of \( k \)-th priority, where \( n_{ik} \) is the partial queuing system capacity, \( n = (n_{ik}) = 1, 2, \ldots, N_{MS}; k = 1, 2, \ldots, K \), \( N_{MS}, K \) are the quantities of the mobile stations MS and priority classes accordingly. As in [5], the stochastic graph of the \( ik \)-th partial queues is shown in Fig. 3.

\[
Q_{ik}(Q) = G_{ik}[1 - r_{Gk}(Q)]\alpha_{ik}/[\tilde{q}_{REQ}(1 - r_{ik}(Q))],
\]

(11)

where \( \alpha_{ik} \) is the mixed negative acknowledgments (ACK) factor, accordingly to stochastic graph

\[
\alpha_{ik} = [1 - (1 - \tilde{q}_{PAC}q_{ACK})^{J/i}] / \tilde{q}_{PAC}\tilde{q}_{ACK},
\]

(13)

As in stochastic graph (Fig. 3), the service cycles presents the sum of a large number of rare random intervals which satisfy to the condition of the limit theorems. One can show that the probability function of the service cycle can be approximated by exponential law [5]. These assumptions are also verified by simulations. Hence, we can obtain the long-delay MAC probability-time and QoS realistic parameters using the known queuing system model \( M / M / m / n_{ik} \), where \( m \) is equal to the sliding window (6).

V. NUMERICAL RESULTS

Fig. 4 illustrates the time tolerance abilities of the PCP MAC with pre-determined superframes RFS. An increase of the round-trip delay (RTD) is expressed in increasing values of sliding windows (6).

We see that RFS MAC guarantee the time tolerance, i.e., the rise of RTD does not degrade the delay and throughput characteristics. Delay constitutes only a transport delay.

The comparison of the dynamic control abilities of the RAS and the RFS MACs’ is shown on Fig. 5.
balance (curves) well coincide with outcomes of a simulation [4]. The graphs obtained by a method of the load intensity adaptation/suppress the/suppress number/suppress J/suppress of/suppress the/suppress data/suppress slots/suppress (so-called/suppress J-MAC/current/packet delay/suppress the/dynamic on-the-fly/control) is characterized by dynamical instability. In contrast, the RAS MAC superframe epoch will be dynamically adapted to current data packets’ flow automatically.

Accordingly to the RFS dependences, to minimize the RFS-MAC current packet delays - the dynamic (on-the-fly) adaptation of the number J of the data slots (so-called J-hopping) is necessary. As shown in [4], this J-hopping on-the-fly control is characterized by dynamical instability. In contrast, the RAS MAC superframe epoch will be dynamically adapted to current data packets’ flow automatically.

Fig. 6 shows the soft QoS multiservices characteristics provided by adaptive CCP MAC reservation protocol (RAS) [4]. The graphs obtained by a method of the load intensity balance (curves) well coincide with outcomes of a simulation (symbols).

VI. CONCLUSIONS

The key challenges of the QoS-oriented satellite MAC technology are conditioned by long-delay space medium. They represent phenomena of MAC’s performance degradation (“time barrier”) and dynamical instability (“dynamic barrier”) which appear when the propagation time increases. We showed that the delay-tolerant abilities depend on the processing algorithm of MAC commands. The new numeric-analytical method for analysis of these phenomena, and also the satellite MAC delay-tolerant abilities has been presented. Based on this method, a theoretical analysis and comparison of the delay tolerance of QoS-oriented satellite MAC reservation protocols with fixed (RFS) and adaptive (RAS) superframes have been developed. The performance comparison has shown that the RAS MAC protocol guarantees best delay tolerance ability.

ACKNOWLEDGMENTS

The author is very grateful to Dr. Igor Sheinman for the valuable contribution to simulation. He also would like to thank Ms. Vera Drozdova for the help in the numerical researches.

REFERENCES