Performance Analysis of a PRMA Protocol Suitable for Voice and Data Transmissions in Low Earth Orbit Mobile Satellite Systems

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Abstract—Mobile satellite systems (MSSs) are expected to play a significant role in providing users with communication services worldwide. In such context, low earth orbit (LEO) satellite constellations seem to be a good solution to attain a global coverage and to allow the use of low-power lightweight mobile terminals. This paper analyzes the performance of a novel medium access control (MAC) scheme suitable for applications in LEO-MSSs, named Packet Reservation Multiple Access with Hindering States (PRMA-HS), that has been derived by proper modifications of the well-known PRMA protocol. We envisage a mixed traffic with voice sources and data sources with different quality of service (QoS) requirements. The good behavior of the proposed PRMA-HS scheme is validated by extensive comparisons with the classical PRMA protocol. Finally, it is shown here that PRMA-HS efficiently supports integrated voice and data traffics in LEO-MSSs.

Index Terms—Mobile satellite systems, multiple access, network architectures and protocols.

I. INTRODUCTION

Future global-coverage mobile networks will integrate a terrestrial cellular segment and a satellite one partly (or totally) based on low earth orbit-mobile satellite systems (LEO-MSSs) [1]–[3]. This paper focuses on medium access control (MAC) protocols and proposes a modification to the Packet Reservation Multiple Access (PRMA) scheme to support both voice and data traffics in LEO-MSSs. Since satellites are power and bandwidth limited, their resources must be efficiently exploited. Hence, a voice terminal must transmit only during a talkspurt, by means of an activity detection scheme, so that variable bit-rate traffic is produced. Moreover, in order to increase the resource exploitation of future MSSs, it is crucial that the bandwidth unused by voice traffic be assigned to data traffics that have not stringent delay requirements (e.g., traffics produced by e-mail and Web browsing applications) [4]. Therefore, in our satellite scenario, the isochronous voice traffic well fits the real-time variable bit rate (rt-VBR) class, whereas the data traffic is of the available bit rate (ABR) type [5].

II. TRAFFIC SOURCE MODELS

This section describes the adopted traffic models for both VTs and DTs. In the following, we denote by $T_f$ the frame duration, by $R_c$ the channel transmission bit-rate and by $R_b$ the voice source bit-rate.

A. Voice Source Model

Each VT uses a speech activity detector (SAD); talkspurts and silent phases are assumed exponentially distributed with mean values $t_1 = 1$ s and $t_2 = 1.35$ s, respectively [7]. The voice activity factor is $\psi_v = (t_1/(t_1 + t_2)) \approx 0.425$. An active VT generates one packet per frame. Each packet encompasses $L_{pkt} = R_cT_f$ information bits and $H$ header bits. There are $N = \lfloor R_cT_f/(L_{pkt} + H) \rfloor$ slots/frame, where $\lfloor . \rfloor$ is the floor function and the slot duration is $T_s = T_f/N$. The VT behavior is described by: the probability that a silent gap ends in $T_s$, $\gamma_v$; the probability that a talkspurt ends during the channel transmission bit-rate and by $\gamma_s$. The PRMA scheme is based on time-division multiple access (TDMA) and combines random access with slot reservation [6], [7]. With PRMA, a voice terminal transmits its packets on a reserved slot only during a talkspurt. When a new talkspurt starts, the terminal uses a permission probability scheme [7] to attempt transmissions. In terrestrial microcellular systems, the terminal promptly receives the outcome of an attempt (feedback channel), since the round trip propagation delay (RTD) is much lower than the packet transmission time [7]. This is not true in LEO-MSSs, where RTD ranges from 5 to 40 ms, depending on the satellite constellation altitude and the minimum elevation angle. If the access packet experiences a collision (we neglect the capture effect [7]), the terminal knows only after RTD that it must reschedule a new attempt. This delay significantly reduces the PRMA efficiency in managing rt-VBR traffics in LEO-MSSs [8], [9]. We propose here a modified PRMA protocol, where a terminal may attempt transmissions also while it is waiting for the outcome of a previous attempt. If that attempt has been unsuccessful, a faster access is achieved. Otherwise, further attempts are useless and may hinder the accesses of other terminals. Hence, this scheme has been called PRMA with hindering states (PRMA-HS). We consider $M_v$ voice terminals (VTs) and $M_d$ data terminals (DTs) per PRMA-HS carrier in a cell that use distinct permission probabilities (different service priorities). Each user terminal (UT), i.e., a VT or a DT, has a buffer to store packets to be transmitted.
the probability that a talkspurt ends within \(T_f, \gamma_f\). Their expressions can be found in [7], where they are respectively denoted by \(\sigma, \gamma, \gamma_f\). The first packet in the VT buffer is discarded if its transmission delay exceeds a specified maximum value, \(D_{\text{max}}\). Typically, \(D_{\text{max}} = 32\) ms [7]. When a packet is discarded, the VT tries to obtain a reservation with the next packet. Let \(P_{\text{drop}}\) denote the packet dropping probability for a VT; it is required that \(P_{\text{drop}} \leq 1\%\) for an acceptable speech quality. The voice throughput is \(\eta_v = M_d/\nu_v(1-P_{\text{drop}})/N\) pkts/slot.

### B. Data Traffic Source Models

Two different DT traffic models have been considered: a Poisson traffic [10] and a WWW browsing one [11], [12]. We assume that the packets of a message arrive simultaneously and synchronized with slot times. Let \(L_d(L_{d,\text{pkts}})\) denote the mean message length in packets (bits, information part). We have

\[
L_{d,\text{pkts}} = \frac{\text{bits}}{\text{msg}}.
\]

The DT performance parameter is measured by the average message delay, \(T_{\text{msg}}\), i.e., the mean time from the message arrival to the DT buffer to the instant when this message is completely sent.

In the Poisson traffic case each DT (i.e., a Poisson DT) generates messages independently of other DTs and according to a Poisson arrival process with mean rate \(\lambda\) msgs/s. Assuming \(XT_s \ll 1\), we can neglect the possibility that a Poisson DT produces more than one message per slot. Hence, a DT generates one message in a slot with probability \(\sigma_d = X T_s\). The message length in packets, \(L_d\), is geometrically distributed with expected value \(L_d = 1/\gamma_d\)

\[
\text{Prob}(\text{message length } L_d = n \text{ pkts}) = \gamma_d (1 - \gamma_d)^{n-1}, \quad n = 1, 2, \ldots.
\]

A DT generating WWW browsing traffic (i.e., a WWW browsing DT) produces packet calls separated by a reading time during a browsing session [11], [12]. A geometrically distributed number of datagrams (= messages) with mean \(N_{\text{pc}}\) is generated per packet call and the datagram interarrival time is exponentially distributed with mean rate \(\mu_{\text{pkt}}\). The reading time is exponentially distributed with mean rate \(\mu_{\text{rdl}}\). The DT activity factor is \(\psi_{\text{dt}} = \frac{(N_{\text{pc}}/\mu_{\text{pkt}})/((N_{\text{pc}}/\mu_{\text{pkt}}) + 1/\mu_{\text{rdl}})}{25/(25 + 8q)}\) and the mean datagram arrival rate is \(\lambda = \mu_{\text{pkt}}/\psi_{\text{dt}}\) msgs/s. We will use [12]: \(N_{\text{pc}} = 25\) msg/packetcall, \(\mu_{\text{rdl}} = 0.25\) s\(^{-1}\) and \(\mu_{\text{pkt}} = 2q\) msg/s, where \(q \in \{1, 2, 3, 4, 5, 6, 7\}\). The datagram length has the same truncated and discretized Pareto distribution shown in [11], [12], where \(L_{d,\text{pkts}} = 3848\) bits/msg.

### C. Stability Considerations on the Terminal Buffer

We consider here the DT buffer stability (VT buffers have no stability problem, since VTs drop the packets that experience an excessive delay). Referring to a DT with a reservation, the mean number of packets produced by the DT per frame, \(\rho_{d-\text{msg}}\), must be lower than 1 in order to guarantee buffer stability

\[
\rho_{d-\text{msg}} = \lambda T_s L_d N < 1 \left[ \frac{\text{pkts}}{\text{frame}} \right].
\]

Moreover, we consider the VT influence on the DT buffer stability: the sum of the voice throughput \(\eta_v\) and data throughput \(\eta_d\) in packets per slot must be lower than one. Assuming the DT buffer stability, \(\eta_d\) must be equal to the total mean input data traffic: \(\rho_d = \lambda T_s L_d M_d\) pkts/slot. Therefore, we have

\[
\lambda T_s L_d M_d + \eta_v < 1 \left[ \frac{\text{pkts}}{\text{slot}} \right],
\]

Conditions (3) and (4) must be jointly used to characterize the DT buffer stability. Hence, we obtain the following upper bound for \(\rho_d\): \(\rho_d_{\text{max}} = M_d/\max(N, M_d)\) pkts/slot. The data goodput, \(G_d\), [13] is

\[
G_d = \frac{\rho_d}{\rho_d_{\text{max}}} = \lambda T_s L_d N M_d, \quad G_d \in [0, 1).
\]

The greater \(G_d\) (under the constraint \(P_{\text{drop}} \leq 1\%\) for VTs), the higher the PRMA-HS efficiency.

### III. Protocol Description and System Modeling

We assume that RTD is equal to its maximum value, \(\text{RTD}_{\text{max}}\), for a given LEO satellite constellation (conservative case). Moreover, the satellite antenna is electronically steered to point to a given area on the earth for all the satellite visibility time (we neglect UT cell changes) [3]. The satellite acknowledges the packet used for the reservation as soon as it correctly decodes its header. We assume \(T_f = n \text{RTD}_{\text{max}} + \varepsilon\), with \(n \geq 1\) and \(\varepsilon\), the packet header transmission time, equal to \(H/R_c\); a UT receives the outcome of its transmission attempt made on a slot before the same slot in the next frame. Since \(\varepsilon \ll \text{RTD}_{\text{max}}\), we have \(T_f \approx \text{RTD}_{\text{max}}\). We consider integer values of \(n\) that divide \(N\) (i.e., \(\text{RTD}_{\text{max}}\) contains \(N/n\) slots).

PRMA-HS allows that a UT may perform new access attempts also while it waits for receiving the outcome of a previous attempt. We assume that the satellite discards any successful reservation attempt after the first one. Note that the voice permission probability \(p_v\) is greater than the data permission probability \(p_d\) in order to prioritize VTs with respect to DTs. We have also assumed an exhaustive service discipline: a UT notifies the satellite of its reservation release by setting an end of reservation flag in the header of the last packet in its buffer.

The PRMA-HS protocol can be described by means of VT and DT behaviors, modeled according to the discrete-time Markov chains in Figs. 1 and 2 (symbols \(A_v, A_d, U_v\) and \(U_d\) will be defined later in this Section), where state transitions occur at the end of each slot. Let us focus on the VT state diagram in Fig. 1. As soon as a UT in a silent pause (SIL) generates the first packet of a new talkspurt, it enters the contending state (CON) and transmits that packet on the first idle slot according to the permission probability \(p_v\). If the VT attempt has been unsuccessful, the VT remains in the CON state and can attempt again on successive idle slots; otherwise, the VT leaves the state and goes into a block of \(N/n\) hindering
states from HIN\((N - 1)\) to HIN\((N - (N/n))\) that model the delay of \(N/n\) slots to receive the positive acknowledgment from the satellite. During the time spent in the hindering states, the VT may still try to transmit on available slots, but its attempts are useless. In the HIN\((N - (N/n))\) state the VT receives the positive acknowledgment from the satellite; thus, the VT enters the block from RES\(^I\)(\(N - (N/n) - 1\)) to RES\(^I\)(1) that models the time of \(N - (N/n) - 1\) slots that is spent waiting for transmitting on the reserved slot (when the VT reaches RES\((0)\)). If this is the last packet of the talkspurt, the VT comes back to SIL, otherwise the VT goes to RES\((N - 1)\).

Since a DT can also receive messages while it is transmitting a given message, a two-dimensional Markov chain is required to model the DT behavior (Fig. 2). This chain has an infinite number of states; each column of states is for a given number \(j\) of messages in the DT buffer. A single state in the VT diagram corresponds to a row of states in the DT diagram (except for IDLE and SIL states). State variables are defined in Table I; in some cases aggregated variables are considered.

In Fig. 1, \(A_v\) is the probability that a VT finds an unreserved slot and obtains the permission to transmit. An analogous definition is valid for \(A_d\) in Fig. 2. We have

\[
A_v = p_v P_f
\]
\[
A_d = p_d P_f
\]

where \(P_f = 1 - \frac{(R_v^d + R_d^v + H_v + H_d)/N)}{}\) is the probability that a slot is not reserved.

A VT will obtain the reservation of a slot if no other UTs in CON or HIN states will attempt to transmit on the same slot. Hence, the probability of a successful transmission attempt for a VT, \(U_v\), is shown in (8) at the bottom of the page. The probability of a successful transmission attempt for a DT, \(U_d\), is shown in (9) at the bottom of the page.

IV. System Analysis

The standard methods for discrete-time Markov chains [14] cannot be used here, since the PRMA-HS state vector (i.e., the

\[
U_v = \begin{cases} 
(1 - p_d) C_d + H_d (1 - p_v) C_v + H_v - 1, & \text{if } C_v \geq 1, \forall C_d, H_v, H_d \\
0, & \text{if } C_v = 0, \forall C_d, H_v, H_d
\end{cases}
\]

(8)

\[
U_d = \begin{cases} 
(1 - p_v) C_v + H_v (1 - p_d) C_d + H_d - 1, & \text{if } C_d \geq 1, \forall C_v, H_v, H_d \\
0, & \text{if } C_d = 0, \forall C_v, H_v, H_d
\end{cases}
\]

(9)
number of UTs in each state of the diagrams in Figs. 1 and 2) has infinite entries. Hence, we have adopted the equilibrium point analysis (EPA) [15] to study the system at an equilibrium point, where the expected rate at which UTs leave a state is equal to the expected rate at which UTs enter the same state [7]. The equilibrium values (small letters) are:

- $s_{VT}$, $s_{DT}$ = equilibrium number of VTs, DTs respectively in SIL and IDLE state.
### TABLE I
**DEFINITION OF THE STATE VARIABLES**

<table>
<thead>
<tr>
<th>State variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_j$</td>
<td>Number of VTs in the CON state</td>
</tr>
<tr>
<td>$C_d$</td>
<td>Number of DTs in all the CON states</td>
</tr>
<tr>
<td>$R'_v$</td>
<td>Number of VTs in RES and RES' states (these VTs know to have a reservation)</td>
</tr>
<tr>
<td>$R'_d$</td>
<td>Number of DTs in RES and RES' states (these DTs know to have a reservation)</td>
</tr>
<tr>
<td>$H_v$</td>
<td>Number of VTs in all the HIN states</td>
</tr>
<tr>
<td>$H_d$</td>
<td>Number of DTs in all the HIN states</td>
</tr>
<tr>
<td>$S_v$</td>
<td>Number of VTs in the SIL state</td>
</tr>
<tr>
<td>$S_d$</td>
<td>Number of DTs in the IDLE state</td>
</tr>
</tbody>
</table>

1. $c_{0v}, c_{0d} = \text{equilibrium number of VTs in the CON state, equilibrium number of DTs totally present in } CON(j)\text{ states for } j = 1, \ldots, \infty$; $c_{0v} = \sum_{j=1}^{\infty} c_{j}(j)$, where $c_{j}(j)$ is the equilibrium number of DTs in $CON(j)$;

2. $h_{0v}(i), h_{0d}(j, i) = \text{equilibrium number of VTs in the HIN}(i)\text{ state, equilibrium number of DTs in the HIN}(j, i)\text{ state, where } j = 1, \ldots, \infty\text{ and } i = N - (N/n), \ldots, N - 1.$ We define: $h_{0v}(i) = \sum_{j=1}^{\infty} h_{d}(j, i) \forall i = N - (N/n), \ldots, N - 1;$

3. $r_v'_{1}(i), r_d'(j, i) = \text{equilibrium number of VTs in the RES}^{1}(i)\text{ state, equilibrium number of DTs in the RES}^{1}(j, i)\text{ state, where } j = 1, \ldots, \infty\text{ and } i = 1, \ldots, N - (N/n) - 1.$ We define: $r_v'_{1}(i) = \sum_{j=1}^{N-1} r_{d}(j, i) \forall i = 1, \ldots, N - (N/n) - 1;$

4. $r_v'_{1}(i), r_d'(j, i) = \text{equilibrium number of VTs in the RES}^{1}(i)\text{ state, equilibrium number of DTs in the RES}^{1}(j, i)\text{ state, where } j = 1, \ldots, \infty\text{ and } i = 0, \ldots, N - 1.$ We define: $r_v'_{1}(i) = \sum_{j=1}^{N-1} r_{d}(j, i) \forall i = 0, \ldots, N - 1;$

5. $r_v'_{1}(i), r_d'(j, i) = \text{denotes the total number of UTs that know to have a reservation and } h_{d}\text{ the total number of UTs in hindering states: } r_v'_{1}(i) = r_{v1} + r_{d1} + r_{d2} + r_{d3} + h_{d}$

The previous sums that define $c_{0v}, h_{0d}(i), r_v'(i)$ and $r_d'(i)$ are convergent, since the total number of DTs in the system is finite. The equilibrium values are real nonnegative numbers that can be derived by equating the inflow and the outflow for each possible state for VTs and DTs, as shown below.

**Voice Subsystem:**

- Equilibrium at the SIL state
  \[ s_v'_{0v} = \gamma_{c}c_{0v} + \gamma_{f_v}r_v'_{1}(0) \] (10)

- Equilibrium at the CON state
  \[ h_v'(i) = h_v'(i+1) = h_v \] (11)

- Equilibrium at the HIN(i) states,
  \[ a_vu_{v}c_{0v}(1 - \gamma_{c}) = h_v \left( \frac{N - n}{n} \right) \] (12)

- Equilibrium at the RES(i) states,
  \[ r_v'(i) = r_v'(i+1) = r_v \] (13)

**ADDENDUM:**

[2] Formulas (19) and (20) are the expressions that at equilibrium correspond to $A_v$ and $U_v$ respectively given in (6) and (8).
dundant. Moreover, the sum of the number of VTs in all the states must be equal to \( M_v \); hence, from (12)–(17), we have

\[
M_v = s_v + c_v + N(r_v + h_v).
\]  

(21)

**Data Subsystem:** The flow equilibrium conditions for the states in Fig. 2 are summed for the states on the same row (e.g., \( \text{CON}(j) \) states, for \( j = 1, \ldots, \infty \)). We obtain the following conditions:

**Equilibrium at the IDLE state**

\[
s_v N_d = (1 - \sigma_d) \gamma_f d \sigma_d (1, 0)
\]

(22)

**Sum of the equilibria at all \( \text{CON}(j) \) states**

\[
(i c_v, j = 1, \ldots, \infty) = h_d \quad \text{if } i = N - \frac{N}{n}, \ldots, N - 2
\]

(23)

Sum of the equilibria at all \( \text{HIN}(j, \infty) \) states

\[
(i c_v, j = 1, \ldots, \infty) \quad \text{if } i = N - \frac{N}{n} - 1
\]

(24)

**Sum of the equilibria at all \( \text{HIN}(j, N - 1) \) states**

\[
(i c_v, j = 1, \ldots, \infty) \quad \text{if } i = N - \frac{N}{n} - 2
\]

(25)

**Sum of the equilibria at all \( \text{RES}(j, i) \) states**

\[
(i c_v, j = 1, \ldots, \infty, i = N - \frac{N}{n} - 1)
\]

(26)

**Sum of the equilibria at all \( \text{RES}(j, N - 1) \) states**

\[
(i c_v, j = 1, \ldots, \infty, i = N - \frac{N}{n} - 2)
\]

(27)

**Sum of the equilibria at all \( \text{RES}(j, 0) \) states**

\[
(i c_v, j = 1, \ldots, \infty, i = N - \frac{N}{n})
\]

(28)

**Sum of the equilibria at all \( \text{RES}(j, 1) \) states**

\[
(i c_v, j = 1, \ldots, \infty, i = N - \frac{N}{n} - 1)
\]

(29)

where, \(^3\) similarly to (19) and (20), we have considered (31) and (32) at the bottom of the page.

If we substitute the expressions in (24), (26)–(29) into (23), (25), and (30), we obtain three equations; through algebraic manipulations, these three equations give (22) that, therefore, is redundant. Hence, we have three equations with five unknown data subsystem variables: \( s_d, c_d, r_d, h_d, r_d(1, 0) \). We add two conditions. We impose that the number of DTs in all the states is \( M_d \). From (24)–(29), we have

\[
M_d = s_d + c_d + N(r_d + h_d).
\]

(33)

Assuming that (3) and (4) are fulfilled, we impose the DT buffer stability: \( \eta_d = \rho_d = \lambda T_s L_d M_d \text{ pkts/slot} \). But \( \eta_d = r_d + h_d \), i.e., the total ongoing flux to \( \text{RES}(j, 0) \) states from (24)–(29). We have

\[
r_d + h_d = \lambda T_s L_d M_d \left[ \frac{\text{pkts}}{\text{slot}} \right].
\]

(34)

Through some algebraic manipulations, (11)–(21) for VTs and (23)–(34) for DTs can be simplified in the following EPA system where \( c_v, c_d, h_v, h_d \) are unknown terms:

\[
\begin{align*}
M_v &= \left(1 + \frac{\gamma_v}{\sigma_v}\right) c_v + \left[\frac{1}{\sigma_v} + \frac{N}{\gamma_f v}\right] h_v \\
M_v &= (1 - \gamma_v) c_d \eta_d v \\
M_v &= \left(1 - \frac{h_v}{\gamma_f v}\right) \left[\frac{\lambda T_s L_d (c_d + h_d)}{1 - \lambda T_s L_d N}\right]
\end{align*}
\]

(35)

(36)

(37)

\[
M_d = \frac{c_d + h_d}{1 - \lambda T_s L_d N}
\]

(38)

Since \( \eta_d \) and \( u_d \) have transcendental expressions, (35)–(38) have been solved with the recursive Gauss–Newton method [16]. Once (35)–(38) is solved, \( r_d(1, 0) \) is obtained from (23)–(30) as \( h_d/[1 - \gamma_d(1 - \sigma_d)r_d]\). The EPA solution is acceptable only if it gives nonnegative equilibrium variable values that fulfill conditions (3) and (4), where \( r_v \) is obtained from EPA as the total ongoing flux to \( \text{RES}(0) \) states:

\[
p_v = r_v + h_v.
\]

A graphical approach can be also considered for the EPA system: for a given couple \( (c_v, c_d) \in \mathbb{R}^+ \times \mathbb{R}^+ \), we numerically solve (36) and (38) to obtain \( u_d = h_d = \frac{h_v(c_v, c_d)}{h_v(c_v, c_d)} \) and

\[
\begin{align*}
a_d &= p_v \left(1 - \frac{r_v^* + h_d}{N}\right) \\
u_d &= \left\{ \begin{array}{ll}
(1 - p_v) c_v + (N/n) h_v & \text{if } c_d \geq 1, c_v, h_v, h_d \\
(1 - p_v) c_v + (N/n) h_v & \text{if } 0 < c_d < 1, c_v, h_v, h_d \\
0 & \text{if } c_d = 0, c_v, h_v, h_d
\end{array} \right.
\end{align*}
\]

(31)

(32)

\( ^3 \) Due to the peculiarities of the transitions from \( \text{RES}(j, 0) \) states in the DT diagram, the ongoing flux to all \( \text{RES}(j, N - 1) \) states is equal to the ongoing flux to all \( \text{RES}(j, 0) \) states, \( r_d(1, 0) \), minus the flux from \( \text{RES}(1, 0) \) to IDLE, \( \gamma_d(1 - \sigma_d)r_d(1, 0) \).

\( ^4 \) Once \( c_v \) and \( c_d \) are fixed, we have verified by a graphical approach that the subsystem (36), (38) admits a single solution.
The conditioned probability that a VT successfully transmits a packet on a slot, \( P_{s,v}(C_v, C_d, H_v, H_d, R^*_v, R^*_d) \), is

\[
P_{s,v}(C_v, C_d, H_v, H_d, R^*_v, R^*_d) = A_v U_v \quad (39)
\]

where \( A_v \) is shown in (6) \( U_v \) is given by (8) and we consider \( C_v + 1 \) VTs in the CON state.

The random number of slots spent by a VT in the CON state to obtain a reservation conditioned on \( \{C_v, C_d, H_v, H_d, R^*_v, R^*_d\} \), \( t_{\text{CON}-v}(C_v, C_d, H_v, H_d, R^*_v, R^*_d) \), has the following geometric distribution:

\[
P_{\text{CON}-v}(k) = P_{s,v}(C_v, C_d, H_v, H_d, R^*_v, R^*_d) \times \left[ 1 - P_{s,v}(C_v, C_d, H_v, H_d, R^*_v, R^*_d) \right]^{k-1}, \quad \text{for } k = 1, 2, \ldots \quad (40)
\]

Hence, \( P_{\text{drop}}(C_v, C_d, H_v, H_d, R^*_v, R^*_d) \) is obtained as follows [7]:

\[
P_{\text{drop}}(C_v, C_d, H_v, H_d, R^*_v, R^*_d) = \left[ 1 - \left( 1 - P_{s,v}(C_v, C_d, H_v, H_d, R^*_v, R^*_d) \right)^D_d \right], \quad \text{for } H_v + H_d + R^*_v + R^*_d < N \quad (41)
\]

where \( D_d = \lfloor D_{\text{max}}/T_s \rfloor \) and \( \lfloor \cdot \rfloor \) denotes the ceiling function.

When \( H_v + H_d + R^*_v + R^*_d = N \), we have from (39) that \( P_{s,v}(C_v, C_d, H_v, H_d, R^*_v, R^*_d) \) is equal to 0 and the distribution of \( t_{\text{CON}-v}(C_v, C_d, H_v, H_d, R^*_v, R^*_d) \) in (40) degenerates. This is due to the fact that (39) does not consider that a reserved slot may be released during the access phase. We neglect this aspect for a conservative \( P_{\text{drop}} \) evaluation. Hence, when all the slots are reserved, analogously to [17], we have

\[
P_{\text{drop}}(C_v, C_d, H_v, H_d, R^*_v, R^*_d) = \frac{C_v + 1}{M_v}, \quad \text{for } H_v + H_d + R^*_v + R^*_d = N. \quad (42)
\]

We remove the conditioning on \( P_{\text{drop}} \) by using the distribution \( \Theta(C_v, C_d, H_v, H_d, R^*_v, R^*_d) \). Since, according to our assumptions, there is at least one VT in the CON state, we consider the conditioned distribution

\[
\Theta(C_v, C_d, H_v, H_d, R^*_v, R^*_d) = \Theta(C_v, C_d, H_v, H_d, R^*_v, R^*_d) \left[ 1 - \text{Prob} \{ C_v = 0 \} \right].
\]

On the basis of the Appendix, we have \( \text{Prob} \{ C_v = 0 \} = 1/(C_v + 1) \). Hence, \( P_{\text{drop}} \) results in (43) at the bottom of the page, where

\[
P_{\text{drop}} = \sum_{R^*_v=0}^{R^*_v} \sum_{R^*_d=0}^{R^*_d} P_{\text{drop}}(C_v, C_d, H_v, H_d, R^*_v, R^*_d) \times \frac{\Theta(C_v + 1, C_d, H_v, H_d, R^*_v, R^*_d)}{(C_v + 1)} \quad (43)
\]
is the maximum number of slots that can be reserved by VTs: \( K_v \) cannot exceed the number of slots per frame and the number of VTs that can have a reservation\(^5\), i.e., \( M_v - 1 \);

\[ K_v = \min\{N, M_v - 1\} \]

\( T_d \) is the maximum number of slots that can be reserved by DTs: \( T_d \) cannot exceed the number of DTs in the system and the number of slots per frame not reserved by VTs;

\[ T_d = \min\{N - R^u, M_d\} \]

\( Z_v \) is the maximum number of VTs in HIN states: \( Z_v \) cannot exceed the maximum possible number of UTs in hindering states, \(^6\) the number of unreserved slots and the number of VTs without a reservation minus one, \(^7\), i.e., \( M_v - R^u - 1 \);

\[ Z_v = \min\{N/n_d, (N - R^u - R^d) - H_v\}, (M_v - R^u - 1)\} \]

\( Q_d \) is the maximum number of DTs in HIN states: \( Q_d \) cannot exceed the maximum possible number of UTs in hindering states, \(^8\) the number of unreserved slots and the number of DTs without a reservation;

\[ Q_d = \min\{N/n_d, (N - R^u - R^d - H_v), (M_d - R^d)\} \]

\( X_v \) is the maximum number of VTs in the CON state: \( X_v \) is equal to the number of VTs in the system minus those already having a reservation minus one; \(^9\)

\[ X_v = M_v - H_v - R^u - 1 \]

\( Y_d \) is the maximum number of DTs in CON states: \( Y_d \) is equal to the number of DTs in the system minus those already having a reservation.

We consider here Poisson DTs to analyze \( T_{\text{msg}} \). Hence, the management of messages in each DT buffer can be modeled as an \( M/G/1 \) queuing system (\( M \): Poisson arrival process /\( G \): general service time distribution/1 server since a DT can transmit a message at once with one slot reservation) with different message service times, whether a message arrives at an empty DT buffer or not (in this case this message does not experience an access delay). We embed the queueing system at the message transmission completion instants. Let \( x(\tau) \) denote the service time in slots for a message arrived at the DT buffer when it is empty (not empty). From the \( M/G/1 \) theory and the Little’s formula \(^{[14]}\), we have

\[ T_{\text{msg}} = \frac{X_T x^2}{2} + \frac{X_T E[x^2] - E[x^2]}{2 + X_T E[x^2]} \quad \text{[slots]}. \quad (44) \]

Let \( I_d \) denote the random variable of the message length in packets: \( E[I_d] = I_d \). Let \( t_{\text{CON-d}}(C_v, C_d, H_v, H_d, R^u, R^d) \) denote the time spent by a DT in CON states in order to make a successful attempt, assuming that when this DT leaves the IDLE state it finds \( C_v \), and \( C_d \) UTs in CON states, \( H_v \) and \( H_d \) UTs in HIN states and \( R^u \) and \( R^d \) UTs that know to have a reservation. Hence, we express \( x \) and \( \tilde{x} \) as follows:

\[ x = t_d N \quad \text{[slots]} \quad (45) \]
\[ \tilde{x} = x + t_{\text{CON-d}}(C_v, C_d, H_v, H_d, R^u, R^d) - 1 \quad \text{[slots]}. \quad (46) \]

The distribution of \( l_d \) is defined by (2), whereas the distribution of \( t_{\text{CON-d}}(C_v, C_d, H_v, H_d, R^u, R^d) \) is formally given by (40), where subscript \( v \) is replaced by \( d \). The mean and the mean square value of both \( l_d \) and \( t_{\text{CON-d}}(C_v, C_d, H_v, H_d, R^u, R^d) \) are

\[ E[l_d] = \frac{1}{\gamma_{fd}} \]
\[ E[l_d^2] = \frac{2 - \gamma_{fd}}{\gamma_{fd}^2} \]

\[ E[t_{\text{CON-d}}(C_v, C_d, H_v, H_d, R^u, R^d)] = \frac{1}{A_d l_d} \]
\[ E[t_{\text{CON-d}}^2(C_v, C_d, H_v, H_d, R^u, R^d)] = \frac{2 - A_d l_d}{(A_d l_d)^2}. \quad (47) \]

Hence, we obtain \( E[x] \) and \( E[x^2] \) from (45) by using \( E[l_d] \) and \( E[l_d^2] \) given in (47). Whereas, in order to have \( E[\tilde{x}] \) and \( E[\tilde{x}^2] \) from (46), we must remove the conditioning on the state in both \( E[t_{\text{CON-d}}(C_v, C_d, H_v, H_d, R^u, R^d)] \) and \( E[t_{\text{CON-d}}^2(C_v, C_d, H_v, H_d, R^u, R^d)] \). On the basis of (47), these expressions are singular when \( A_d = 0 \) (i.e., all the slots are reserved, \( H_v + H_d + R^u + R^d = N \)). Correspondingly, the distribution of \( t_{\text{CON-d}}(C_v, C_d, H_v, H_d, R^u, R^d) \) degenerates. This is due to the fact that we have neglected the release of slots during the access phase of a UT. Therefore, \( t_{\text{CON-d}}(C_v, C_d, H_v, H_d, R^u, R^d)|H_v + H_d + R^u + R^d = N \) accounts for both the time for the first release of one reservation, \( t_r(C_v, C_d, H_v, H_d, R^u, R^d)|H_v + H_d + R^u + R^d = N \) and the time to obtain a reservation starting from a situation with \( N - 1 \) reserved slots, \( t_{\text{CON-d}}(C_v, C_d, H_v, H_d, R^u, R^d)|H_v + H_d + R^u + R^d = N - 1 \). Hence, we have

\[ t_{\text{CON-d}}(C_v, C_d, H_v, H_d, R^u, R^d)|H_v + H_d + R^u + R^d = N \]
\[ + H_d + R^u + R^d = N \]
\[ = t_r(C_v, C_d, H_v, H_d, R^u, R^d)|H_v + H_d + R^u + R^d = N \]
\[ + H_d + R^u + R^d = N \]
\[ = t_{\text{CON-d}}(C_v, C_d, H_v, H_d, R^u, R^d)|H_v + H_d + R^u + R^d = N - 1 \]. \quad (48) \]

Since \( t_r(C_v, C_d, H_v, H_d, R^u, R^d)|H_v + H_d + R^u + R^d = N \) and \( t_{\text{CON-d}}(C_v, C_d, H_v, H_d, R^u, R^d)|H_v + H_d + R^u + R^d = N - 1 \) are independent variables, we can easily obtain the mean and the mean square value of \( t_{\text{CON-d}}(C_v, C_d, H_v, H_d, R^u, R^d)|H_v + H_d + R^u + R^d = N \). In \( t_{\text{CON-d}}(C_v, C_d, H_v, H_d, R^u, R^d)|H_v + H_d + R^u + R^d = N - 1 \) we assume that \( R^u + R^d \) is reduced by one with respect to \( t_{\text{CON-d}}(C_v, C_d, H_v, H_d, R^u, R^d)|H_v + H_d + R^u + R^d = N \), so that \( A_d = A_d - 1 \); hence, the distribution of \( t_{\text{CON-d}}(C_v, C_d, H_v, H_d, R^u, R^d)|H_v + H_d + R^u + R^d = N - 1 \) is given

\[ 3\]This value takes into account that at least one VT has not a reservation to start a new contending procedure.

\[ 6\]At most, we can have a UT waiting for an acknowledgment for each delay from 1 to \( N/n \) slots.

\[ 7\]This value takes into account that at least one VT has not a reservation to start a new contending procedure.

\[ 8\]At most, we can have a UT waiting for an acknowledgment for each delay from 1 to \( N/n \) slots.

\[ 9\]This value takes into account that at least one VT has not a reservation to start a new contending procedure.
by (40) with subscript \(d\) instead of \(v\). Moreover, we consider that \(t_r(C_v, C_d, H_v, H_d, R_v, R_d) = N\) is geometrically distributed

\[
P_r(k) = p_r(C_v, C_d, H_v, H_d, R_v, R_d) \times \left[1 - p_r(C_v, C_d, H_v, H_d, R_v, R_d)\right]^{k-1},
\]

for \(k = 1, \ldots, (49)\)

where the probability to release the reservation of a slot, \(p_r(C_v, C_d, H_v, H_d, R_v, R_d)\), is obtained as follows: a VT releases the reservation with probability \(\gamma_{v\downarrow}\), whereas a DT releases the reservation with the probability that it has transmitted the last packet of the last message in its buffer and no other message arrival occurs on this slot, \(\gamma_{d\downarrow}(r_d(1, 0)/r_d(0))^{1 - \sigma_d}\). These probabilities are respectively weighted by the probability that the slot is reserved by a VT, \((R_v + H_v)/N\) and by a DT, \((R_d + H_d)/N\). We have

\[
p_r(C_v, C_d, H_v, H_d, R_v, R_d) = \frac{R_d + H_d}{N} \gamma_{d\downarrow}(1 - \sigma_d)
\times \frac{r_d(1, 0)}{r_d(0)} + \frac{R_v + H_v}{N} \gamma_{v\downarrow}. (50)
\]

Finally, we remove the conditioning in \(E[t_{\text{CON}-d}(C_v, C_d, H_v, H_d, R_v, R_d)]\) and \(E[t_{\text{CON}-d}^2(C_v, C_d, H_v, H_d, R_v, R_d)]\) by using the joint state distribution and the normalization factor \(1/[1 - \text{Prob.}(C_v = 0)] = (\mathcal{C}_t + 1)/\mathcal{C}_t\), since at least one DT must be in the contending state (see the Appendix). We have (51) at the bottom of the page.

\[
T_v = \min\{N, M_v\}, \quad K_d = \min\{N - R_v, M_d - 1\},
\]

\[
Q_v = \min\{N/n_v(N - R_v - R_d), (M_v - R_v)\}, \quad Z_d = \min\{N/n_v(N - R_v - R_d - H_v), (M_d - R_d - 1)\},
\]

\[
Y_v = M_v - H_v - R_v, \quad X_d = M_d - H_d - R_d - 1.
\]

VI. RESULTS

Each simulation has been very long (200 \times 10^6 slots) and repeated ten times to obtain reliable results [18]. We focus here on a communication system with \(R_c = 765\) kbps/s, \(R_a = 32\) kbps/s, and \(H = 64\) bits where the EPA system admits only one solution and where (3) and (4) are fulfilled (DT buffer stability).

A. Selection of System Parameter Values

Simulation results have shown that \(P_{\text{drop}}\) has unacceptably high values when \(p_v\) is close to 0 or 1 (for very low \(p_v\) values, VTs do not quickly access slots; while, for very high \(p_v\) values, VTs experience frequent collisions). In general, \(p_v = 0.6\) is a good choice. Moreover, \(P_{\text{drop}}\) slightly depends on \(p_d\) only when \(p_d\) is close to 1, \(P_{\text{drop}}\) increases owing to frequent collisions between DT and VT attempts. When \(p_v\) and \(p_d\) are close to 1, \(T_{\text{msg}}\) exhibits a peak due to frequent collisions; moreover, \(T_{\text{msg}}\) increases when \(p_d < 0.2\), since accesses are delayed. In conclusion, we have set \(p_v = 0.6\) and \(p_d = 0.2\) to prioritize VTs as regards DTs.

Let \(M_{\text{MAX}}\) denote the maximum number of VTs that can be served by a PRMA-HS carrier with \(P_{\text{drop}} \leq 1\%\). Due to the presence of DTs, the quantity \([R_c - \lambda L_{\text{pkt}} M_d]/R_a\) represents the maximum number of slots that can be used by VTs in an ideal TDMA carrier (i.e., without packet overhead). We define the VT multiplexing gain, \(\mu_v\), expressed in conversations/voice channel as the ratio between \(M_{\text{MAX}}\) and \([R_c - \lambda L_{\text{pkt}} M_d]/R_a\). If \(\mu_v > 1\), conversations/voice channel, PRMA-HS achieves a more efficient VT management than the ideal TDMA scheme. Fig. 4 shows \(\mu_v\) behaviors as a function of \(T_f\) (i.e., RTD_{\text{MAX}}, since \(n_1 = 1\)) for a given configuration by using the previously selected values of \(p_v\) and \(p_d\). We note that: 1) PRMA-HS is more efficient than TDMA on a wide range of \(T_f\) values and 2) PRMA-HS outperforms PRMA especially

\[
E[t_{\text{CON}-d}^2] = \sum_{R_v = 0}^{T_v} \sum_{R_d = 0}^{K_d} \sum_{Q_v = 0}^{Z_d} \sum_{Y_v = 0}^{X_d} \sum_{N = 0}^{N} E[t_{\text{CON}-d}^2(C_v, C_d, H_v, H_d, R_v, R_d)] /
\]

\[
\frac{\mathcal{C}_t}{\mathcal{C}_t + 1}
\]

\[
E[t_{\text{CON}-d}] = \sum_{R_v = 0}^{T_v} \sum_{R_d = 0}^{K_d} \sum_{Q_v = 0}^{Z_d} \sum_{Y_v = 0}^{X_d} \sum_{N = 0}^{N} E[t_{\text{CON}-d}(C_v, C_d, H_v, H_d, R_v, R_d)] /
\]

\[
\frac{\mathcal{C}_t}{\mathcal{C}_t + 1}
\]

(51)
from medium to high RTD\textsubscript{max} values. A similar \( \mu_v \) behavior as a function of \( T_f \) can be obtained with WWW browsing DTs. Therefore, \( \mu_v \) of PRMA-HS is high for \( T_f \in [15, 30] \) ms; we choose \( T_f = 15 \) ms (correspondingly \( N = 21 \) slots/frame), since this value allows the lowest \( P_{\text{drop}} \). The following results have therefore been obtained by using \( p_v = 0.6, p_d = 0.2 \) and \( T_f = 15 \) ms.

B. PRMA-HS Performance Evaluation

Figs. 5 and 6 compare simulation and analytical results as a function of \( G_d \) with \( L_{\text{data}} = 2400 \) bits/msg, \( M_v = 21 \) VTs/carrier, \( M_d = 10 \) DTs/carrier, \( L_{\text{data}} = 21 \) VTs/carrier, \( M_d = 10 \) Poisson DTs/carrier and \( n = 3 \); \( G_d \) in abscissa varies due to the message arrival rate increase from 1.4 to 12.6 msgs/s. Fig. 5 shows that \( P_{\text{drop}} \) increases with \( G_d \) and that the theory gives an upper bound sufficiently close to simulation results (especially when \( P_{\text{drop}} \) ranges from \( 10^{-3} \) to \( 10^{-2} \)). The maximum \( G_d \) value with \( P_{\text{drop}} \leq 1\% \) is about equal to 0.9, so highlighting an efficient resource management. Fig. 6 also shows a good agreement between simulation and analytical results for \( T_{\text{msg}} \).

Figs. 7 and 8 show \( P_{\text{drop}} \) and \( T_{\text{msg}} \) behaviors for \( M_v = 21 \) VTs/carrier, \( M_d = 10 \) Poisson DTs/carrier and \( n = 3 \) with \( \mu_d = 0.3 \) and 0.4 pkts/slot as a function of \( L_{\text{data}} \). From Fig. 7, we have that the \( P_{\text{drop}} \) theory allows a conservative estimation, close to simulation results. Moreover, Fig. 8 highlights that the proposed analytical approach for \( T_{\text{msg}} \) yields an accurate estimation.
in the presence of WWW browsing DTs is slightly higher than with Poisson DTs, since the greater the data traffic burstiness the higher the congestion of the contending state. As for $T_{\text{TR}}$, the scale adopted in Fig. 12 does not allow to highlight the advantages (on the order of tens of slots) of PRMA-HS with respect to PRMA (the main contribution to $T_{\text{TR}}$ is due to the datagram queuing rather than to the access phase). Finally, $T_{\text{TR}}$ significantly increases in the WWW browsing case with respect to the Poissonian one, due to both the high datagram length variance and the bursty traffic that causes a sudden queuing of datagrams.

VII. CONCLUSION

In this paper, we have proposed the PRMA-HS protocol to support voice and data traffics in LEO-MSSs. Suitable traffic models have been considered for both voice and data sources. The PRMA-HS performance has been evaluated in terms of packet dropping probability for VTs, $P_{\text{drop}}$, and mean message transmission delay for DTs, $T_{\text{MD}}$. Analytical predictions for both $P_{\text{drop}}$ and $T_{\text{MD}}$ have resulted in agreement with simulation results. In conclusion, it has been highlighted here that PRMA-HS efficiently manages voice and data traffics in LEO-MSSs and clearly outperforms the classical PRMA protocol.

APPENDIX

DERIVATION OF THE JOINT STATE PROBABILITY DISTRIBUTION

Using three times the Bayes rule, the joint state probability distribution $\Theta(C_v, C_d, H_v, H_d, R^v_v, R^d_d)$ is

$$\Theta(C_v, C_d, H_v, H_d, R^v_v, R^d_d) = \Theta(C_v, C_d | H_v, H_d, R^v_v, R^d_d) \times \Theta(H_v, H_d | R^v_v, R^d_d) \Theta(R^v_v | R^v_v) \Theta(R^d_d)$$

(A.1)

where $\Theta(R^v_v)$ is the distribution of $R^v_v$ and where $\Theta(R^v_v | R^v_v)$, $\Theta(C_v, C_d | H_v, H_d, R^v_v, R^d_d)$ are conditioned distributions.

Each slot has the same probability to be reserved and slots are independently reserved by VTs with probability $p_{\text{res}}$. Hence, the probability of $R^v_v$ slots reserved by VTs is binomial

$$\Theta(R^v_v) = \begin{pmatrix} T_v \\ R^v_v \end{pmatrix} (p_{\text{res}})^{R^v_v} (1-p_{\text{res}})^{T_v-R^v_v},$$

$$R^v_v \in [0, T_v]$$

and $T_v = \min \{N, M_v\}$. 

(A.2)
Since we refer to cases with a single EPA solution, we obtain $P_{\text{res},v}$ by equating the mean value of $R^*_v$ to the corresponding equilibrium value. From (11)–(18), we have

$$P_{\text{res},v} = N \left( \frac{1}{T_d} - \frac{1}{N} \right) h_v \frac{H_v}{T_v} . \quad \text{(A.3)}$$

We define $p_{\text{res},d}$ as the probability that a slot is reserved by a DT conditioned on $R^*_d$ slots already reserved by VTs. We consider the following binomial distribution for $\Theta(R^*_d|R^*_v)$:

$$\Theta(R^*_d|R^*_v) = \left( \frac{T_d}{R^*_d} \right) (P_{\text{res},d}) R^*_v (1 - P_{\text{res},d}) T_d - R^*_d , \quad \text{if } R^*_d \in [0, T_d]$$

and $T_d = \min \{ N - R^*_d, M_d \}$ \quad \text{(A.4)}

Probability $P_{\text{res},d}$ is obtained by equating the mean of $R^*_d$ to its equilibrium value

$$P_{\text{res},d} = \frac{N R_d + (N - \frac{N}{n}) h_d}{\sum_{R_v=0}^{T_d} T_v \Theta(R^*_v)} . \quad \text{(A.5)}$$

In order to derive $\Theta(H^*_v, H^*_d|R^*_v, R^*_d)$ we use the Bayes rule as follows:

$$\Theta(H^*_v, H^*_d|R^*_v, R^*_d) = \Theta(H^*_v|H^*_d, R^*_v, R^*_d) \Theta(H^*_d|R^*_v, R^*_d) . \quad \text{(A.6)}$$

Both $\Theta(H^*_v|H^*_d, R^*_v, R^*_d)$ and $\Theta(H^*_d|R^*_v, R^*_d)$ are assumed binomial, since each unreserved slot has the same probability to be successfully occupied by a UT that enters the hindering states. Hence, we have

$$\Theta(H^*_v|H^*_d, R^*_v, R^*_d) = \left( \frac{Q_v}{H_v} \right) (p_{\text{hain},v}) H_v \times (1 - p_{\text{hain},v}) Q_v - H_v , \quad \text{(A.7)}$$

where $p_{\text{hain},v}(p_{\text{hain},d})$ is the conditioned probability that a VT (DT) is in a HIN state (in a row of HIN $(j_i, j_d)$ states). Equating expectations of $H^*_v$ and $H^*_d$ to the corresponding equilibrium values, we have (A9) at the bottom of the page. We made two assumptions for $\Theta(C_v, C_d|H^*_v, H^*_d, R^*_v, R^*_d)$: 1) $C_v$ and $C_d$ are statistically independent and 2) the number of VTs (or DTs) in the CON state is independent of the number of DTs (or VTs) in HIN, RES' or RES states. These assumptions are reasonable in a noncongested system, i.e., when $c_v < 1$ and $c_d < 1$ (as it occurs if $p_{\text{drop}} \leq 1\%$) so that there are few collisions between DT and VT attempts. We have

$$\Theta(C_v, C_d|H^*_v, H^*_d, R^*_v, R^*_d) = \Theta(C_v|H^*_v, R^*_v) \Theta(C_d|H^*_d, R^*_d) \quad \text{(A.10)}$$

where $\Theta(C_v|H^*_v, R^*_v)$ and $\Theta(C_d|H^*_d, R^*_d)$ can be modeled as truncated geometric distributions [9]. See (A11) and (A12) at the bottom of the page. $p_{\text{ov}}$ and $p_{\text{od}}$ respectively denote the probability of no VT and no DT in the contending state. Probabilities $p_{\text{ov}}$ and $p_{\text{od}}$ are derived by equating the expected values of $C_v$ and $C_d$ to their equilibrium values. We have numerically verified that a good approximation for the solution of these equations is

$$p_{\text{ov}} \approx (c_v + 1)^{-1} \quad \text{and} \quad p_{\text{od}} \approx (c_d + 1)^{-1} . \quad \text{(A.13)}$$

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\begin{align}
p_{\text{hain},v} &= \frac{h_v}{N \sum_{R_v=0}^{T_d} R_v \Theta(R^*_v) \Theta(R^*_d)} \quad \text{and} \quad \frac{h_d}{N \sum_{R_v=0}^{T_d} R_v \Theta(R^*_v) \Theta(R^*_d)} \quad \text{(A.9)}

\Theta(C_v|H^*_v, R^*_v) &= \begin{cases} p_{\text{ov}} (1 - p_{\text{ov}}) C_v, & \text{if } C_v < M_v - H_v - R^*_v \\ (1 - p_{\text{ov}}) C_v, & \text{otherwise} \end{cases} \quad \text{(A.11)}

\Theta(C_d|H^*_d, R^*_d) &= \begin{cases} p_{\text{od}} (1 - p_{\text{od}}) C_d, & \text{if } C_d < M_d - H_d - R^*_d \\ (1 - p_{\text{od}}) C_d, & \text{otherwise} \end{cases} \quad \text{(A.12)}
\end{align}
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