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Multiple access in DVB-RCS2 user uplinks

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SUMMARY

Digital Video Broadcasting, Return Channel via Satellite 2 (DVB-RCS2) is the second generation of DVB-RCS communication specification for the return link in broadband interactive geostationary satellite networks. The focus of this paper is the user uplink access mechanism in DVB-RCS2. The first part of the paper provides a brief description of DVB-RCS2 user uplink access, with emphasis on improvements with respect to the first generation of the standard. One of these improvements in DVB-RCS2 is the support for random access (RA) for user traffic. The second part of the paper further delves into the RA load control problem and proposes an analytical model for the DVB-RCS2 RA load control algorithm followed by performance assessment via numerical computations and simulations.

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KEY WORDS: DVB-RCS2; satellite; DAMA; random access; CRDSA

1. INTRODUCTION

This paper first briefly describes the user uplink multiple access mechanisms in Digital Video Broadcasting, Return Channel via Satellite 2 (DVB-RCS2) [1] with emphasis on changes from the first version of the specification [2], which is referred to as 'DVB-RCS' in the paper. Then, a Markov model is proposed for the random access (RA) load control mechanism together with performance analyses based on numerical computations and simulations.

The DVB-RCS2 dictates mandatory[1] support for multi-frequency time division multiple access (MF-TDMA) channel access method on the return link. Thus, transmission bursts from Return Channel via Satellite Terminals (RCSTs) are expected at the gateway (GW) receiver antenna within allocated frequency bands and allocated time intervals—a combination that is referred to as 'timeslots'.[2] DVB-RCS2 supports dedicated access (DA) to these timeslots, where each timeslot is exclusively allocated to an individual RCST. The allocation procedure may be solicited or unsolicited. Solicited allocation is equivalent to the demand assignment multiple access (DAMA) mechanism in DVB-RCS; whereby, RCSTs must send to the NCC volume-based and/or rate-based dynamic CRs before being allocated timeslots. In unsolicited allocation, the NCC allocates timeslots to RCSTs without prior CRs. The NCC may allocate such timeslots to provide a minimum guaranteed rate for each RCST or to share excess return link capacity among RCSTs. Unsolicited allocation is equivalent to CRA and free capacity

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[1]Optionally, DVB-RCS2 may allocate a continuous carrier to an RCST on the return link. This is different from constant rate assignment (CRA) in MF-TDMA. Continuous carrier is out of scope of this paper.
[2]Periodic network clock reference messages on the forward link and closed-loop corrections between an RCST and the Network Control Centre (NCC) of the RCST's timing and carrier errors are essential to ensure that bursts fit in timeslots.

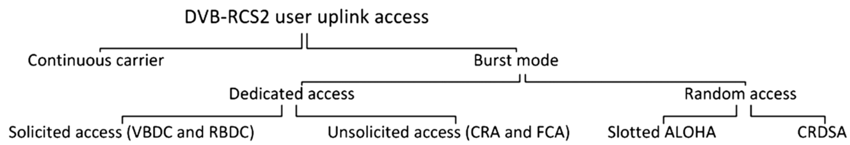

Figure 1. User uplink access mechanisms in DVB-RCS2.

assignment in DVB-RCS. Unlike DVB-RCS, DVB-RCS2 optionally supports RA to return link timeslots for user traffic transmission as well as control and logon traffic. Both slotted ALOHA (SA) [3] and contention resolution diversity slotted ALOHA (CRDSA) [4, 5] are included in the specification with load control procedures for logon, control and user traffic. Also note that implementation-dependent support can be introduced for irregular repetition slotted ALOHA (IRSA [6]) by defining the necessary forward link signalling descriptors in the user space. Figure 1 shows a summary of DVB-RCS2 user uplink access mechanisms.

Section 2 provides a more detailed description of the DVB-RCS2 support for dedicated and RA with emphasis on return link configuration signalling, RA load control and DA CRs. Section 3 describes a Markov model for the DVB-RCS2 RA load control mechanism before evaluating its accuracy via numerical computations and simulation analyses. Section 4 provides a summary of the paper with pointers to future research problems.

2. DEDICATED AND RANDOM ACCESS IN DVB-RCS2

2.1. Return link configuration and signalling

A superframe sequence refers to a specific portion of the user uplink frequency spectrum. It is structured as superframes that are contiguous in time. All superframes in the sequence have the same duration, centre frequency, and bandwidth.

The Superframe Composition Table (SCT) is broadcast regularly on the forward link and specifies the composition of the superframe used in each sequence. A superframe is composed of a number of frames each of a specific frame type, which again are structures that are described in the Frame Composition Tables (FCT2 (Suffix '2' is to distinguish FCT2 in DVB-RCS2 from FCT in DVB-RCS. This is also the case for TBTP2.)) that is also broadcast regularly on the forward link.

The FCT2 contains description of frame types. The frame locations in time and frequency are indicated in the SCT. Fundamental to the frame description is the bandwidth-time unit (BTU), which is a combination of a symbol rate, a frequency bandwidth and a duration. Each frame is structured as a sequence of identical BTUs. A frame type specification may also define timeslots, in which each is a structure of contiguous BTUs with a default tx_type and a fixed_access_method as attributes. The fixed_access_method value, if greater than zero, indicates that a timeslot is used for RA. A zero value indicates that the access for a timeslot is indicated later in Terminal Burst Time Plan (TBTP2) table broadcasted on the forward link. The specification of the timeslot corresponding to a tx_type is provided in the Broadcast Configuration Table (BCT) that also is broadcast regularly on the forward link.

The BCT contains a description of a timeslot type corresponding to a tx_type value, including duration in number of BTUs, the waveform specification and the payload type (i.e. logon, control, traffic and control-and-traffic). The location of a timeslot, as defined by the BCT, within a frame can be specified in the FCT2. This is similar to the relationship between FCT2 and SCT as far as frame locations are concerned.

The assignment of timeslots to individual RCSTs is indicated in the periodic TBTP2 broadcasts on the forward link. Having received both SCT and FCT2, the RCST can unambiguously identify each frame in each superframe. In a superframe, the frames are numbered from 0 (lowest centre frequency, first in start time and lowest in frame type ID) to N (highest centre frequency, last in start time and highest in frame type ID), ordered, with falling precedence, according to ascending centre frequency, ascending start time and then ascending frame type.[3] The TBTP2 can refer to each frame in the

[3]It is possible that the superframe description contains frames that overlap in time and frequency. Yet, this flexible scheme does not pose any problems because the TBTP2 contains slot allocations in only one of these overlapping frames, effectively disabling the others.

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superframe using this numbering scheme and allocate timeslots within selected frames. TBTP2 indicates the assignment_id value for each timeslot. Assignment_id may be an 8-bit, a 16-bit, a 24-bit or a 48-bit identifier that has, as a minimum, a forward-link wide scope. The lower range of assignment_ids (e.g. 0x01-0xF0 with 8-bit assignment_ids) are used for DA, and each assignment_id is uniquely associated to a given DA channel in a given RCST. Multiple DA channels may be defined for an RCST, and hence, multiple assigment_ids may be associated with the same RCST. The upper range of an assignment_id space (e.g. 0xF0-0xFF in 8-bit assignment_ids) may be used to indicate that the referred timeslot is an RA timeslot with the same assignment_id form as an RA channel.

The SCT, FCT2 and BCT are broadcasted regularly. TBTP2 is broadcasted for each superframe. The superframe duration is between 25 and 750 ms. The RCST determines the start of each superframe from the superframe duration, the start time of the superframe reference provided in the SCT and the offset in number of superframes from this reference.

An important improvement over DVB-RCS is that the TBTP2 may be used to define/change the tx_type of a timeslot (defining also controls the timeslot structure of a frame), completing/overriding the value in FCT2. Thus, the timeslot composition may be determined just in time. This arrangement significantly improves the resource allocation dynamicity in the face of time-varying traffic patterns and channel conditions.

Figure 2 shows examples of frame types as these are described in a FCT2. The tx_format_class attribute in FCT2 indicates the transmission format (e.g. linear modulation versus continuous phase modulation) for each frame according to the tx_format_class table in Figure 2.

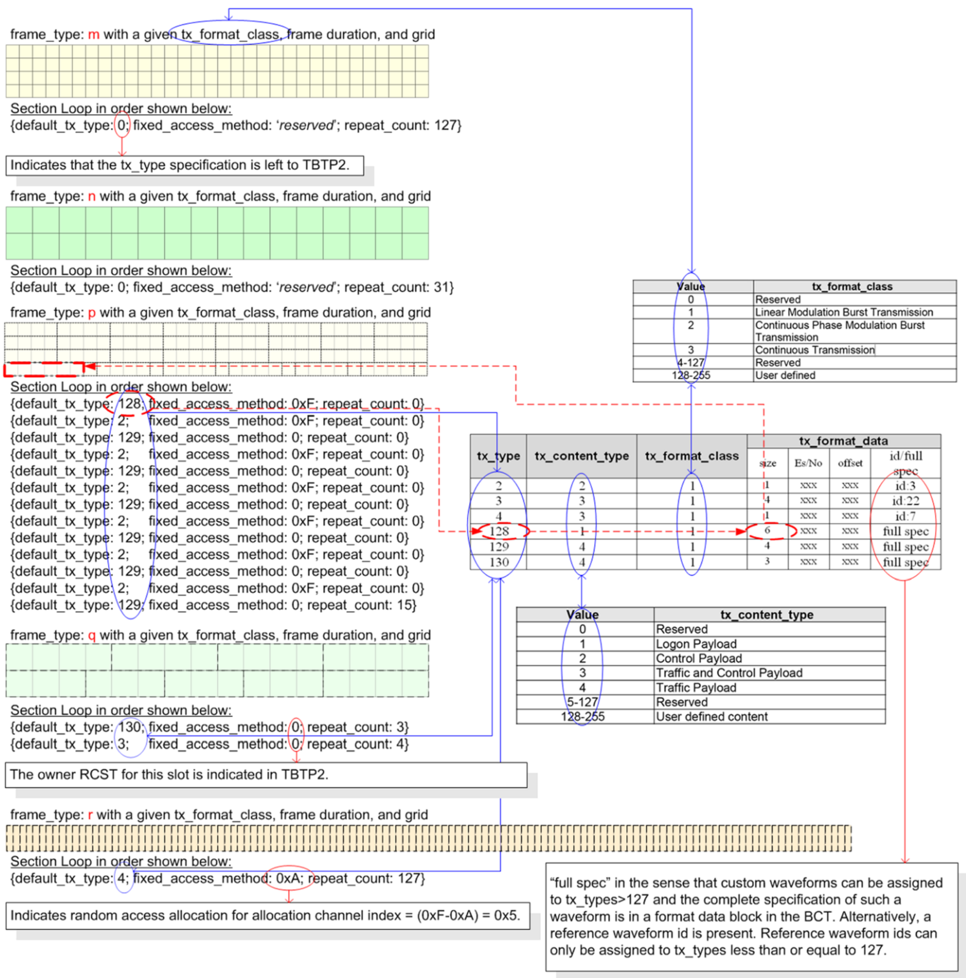

Figure 2. Example frame descriptions in FCT2.

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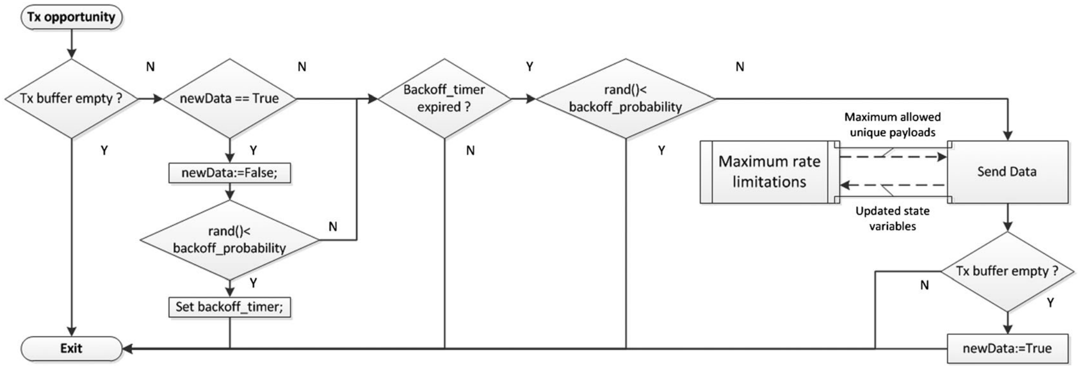

Figure 3. Flow chart describing the load control. Tx opportunity is either a slot in Slotted ALOHA, or an RA block in CRDSA.

In Figure 2, frame_type:m and frame_type:n are grids of 128 and 32 BTUs,[4] respectively. The BTU duration, symbol rate and bandwidth are indicated for each frame within the FCT2. For both frame types m and n in this example, the FCT2 leaves the definition of timeslots to subsequent TBTP2 tables (i.e. default_tx_type:0). In contrast, for frame_type:p and frame_type:q, FCT2 defines timeslots with specific default_tx_types. The BCT resolves the tx_type. The figure shows how a tx_type is associated with tx_content_type (indicating allowed payload content), size (in terms of BTUs) and a waveform specification. Note that a timeslot with a fixed_access_method:0 indicates that the timeslot is to be allocated in a subsequent TBTP2. Alternatively, FCT2 may have non-zero fixed_access_method for a timeslot indicating the RA channel that the slot belongs to. (DA slot allocation can only be done in TBTP2.) In Figure 2, frame_type:p has slots with 0xF fixed_access_method for RA control traffic. The last example frame type in the figure, frame_type:r, contains 128 timeslots belonging to RA channel 0x5. These slots are of default_tx_type:4 and are allowed to carry user traffic (but not control protocol data units (PDUs)).

2.1.1. Random access slots on the return link. For CRDSA and for load control (both for SA and CRDSA), RA block definition is a key concept. RA slots of a given RA channel are grouped in RA blocks according to their locations along the time axis. RA block definition, which is in the broadcast RA traffic method descriptor, indicates the start and the end time of each RA block in each superframe sequence for each RA channel. It is important to note that the RA traffic method descriptor may not contain RA block definitions. In this case, the default RA block duration corresponds to the whole superframe, and all RA slots of the same RA channel in the superframe belong to the same RA block.

Random access blocks are equivalent to CRDSA frames. The RCST randomizes CRDSA replica locations across the RA block. At the GW, the CRDSA decoder applies successive interference cancellation independently across each RA block.

Random access blocks are also used in load control definition for both CRDSA and SA.

2.2. Random access load control for user traffic

In DVB-RCS2, the terminal runs a separate instance of load control for each RA channel. The specification allows using different load control algorithms for different RA channels. In addition to allowing the use of user-defined load control algorithms, the specification defines a normative load control method. (‘Normative’ if the RCST supports random access for user traffic.)

Figure 3 describes the normative load control algorithm for DVB-RCS2 RA data channels. Back_off_probability and back_off_time are the two load control parameters (periodically broadcast in RA load control descriptor for each RA channel). The term ‘transmission opportunity’ is used to

[4]Note that ‘repeat_count’ attribute indicates the number of back-to-back repetitions of a slot (or BTU). This 128 BTUs in the frame is indicated as repeat_count:127.

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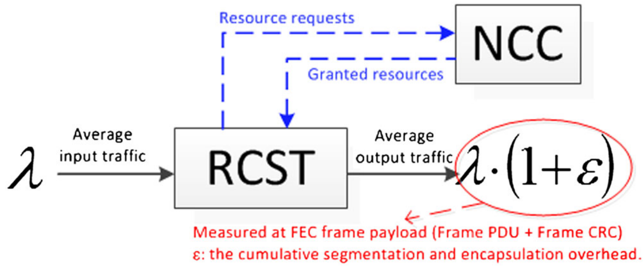

Figure 4. Resource request and allocation.

provide a single load control algorithm description for both CRDSA and SA RA channels. For SA, transmission opportunity refers to each SA timeslot of the RA channel. For CRDSA, transmission opportunity is each RA block of the RA channel. Key to the algorithm is whether or not the data in the transmission buffer has already been partially transmitted on the RA channel. This is maintained in the newData flag. If the data in the transmission buffer is new, the algorithm avoids using the RA channel for a deterministic back_off_time with a back_off_probability. All subsequent transmission opportunities will be bypassed before the backoff timer expires. If the data in the transmission buffer is not new, or if the backoff timer has expired, then the RCST uses each transmission opportunity with a (1-back_off_probability). The number of unique payloads[5] that can be sent in the transmission opportunity is upper bounded such that the maximum rate limitations are not violated. In SA, a transmission opportunity corresponds to one SA slot, and a maximum of one unique payload may be sent. In CRDSA, a transmission opportunity corresponds to one RA block, and more than one unique payload may be sent in each RA block.

The maximum rate limitations are imposed by the rules:

(1) The number of unique payloads sent in each RA block must be lower than max_unique_payload_per_block.
(2) The RCST is not allowed to transmit in a number of consecutive RA blocks that is greater than max_consecutive_blocks_accessed value.
(3) If the RCST has consecutively accessed max_consecutive_blocks_accessed RA blocks, then the RCST must consecutively avoid accessing a min_idle_blocks RA blocks.

The maximum rate limitations process runs independently with load control and defines an envelope of the traffic sent by an RCST on the RA channel. The parameters that define the maximum rate limitations can be assigned individually for each lower layer service in each RCST at the time of logon. Thus, it is possible to provide service segregation among traffic streams (e.g. voice versus layer 2 signalling) over the same RA channel with the same load control parameters.

2.3. DVB-RCS2 dedicated access

Definition of CRA, volume based dynamic capacity (VBDC), absolute VBDC and free capacity assignment in DVB-RCS2 are the same as with DVB-RCS [2] and have their roots in [7]. DA-related modifications in DVB-RCS2 have primarily to do with the CR generation and signalling.

2.3.1. Capacity request generation. The DVB-RCS2, like DVB-RCS, does not define a standard algorithm to generate CRs. This is intentionally left out as an implementation decision. However, in a multi-vendor DVB-RCS2 network with RCSTs possibly running different CR generation algorithms, maintaining resource allocation fairness among RCSTs can be difficult. As a solution, DVB-RCS2 imposes limitation on the level of resources that can be requested. Figure 4 shows conceptually the average input and output traffic at the RCST in the return direction. The output

[5]The layer 2 PDU sent down to the MAC sublayer. In CRDSA, a number of replicas are transmitted for each unique payload in the RA block. In SA, the unique payload is transmitted on its own in the slot.

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traffic also includes the overhead introduced by layer 2 and layer 1 segmentation and encapsulation. The figure also shows resource requests and resource grants between the RCST and the NCC.

The DVB-RCS2 dictates that the RCST must ensure for each request class that

(1) the resources requested (for all capacity categories combined),
(2) the resources accessed via RA and
(3) the resources allocated via CRA

do not exceed the 110% of the resources required to carry the input traffic. In reference to Figure 4, this corresponds to 110% of $\lambda{\cdot}(1+\varepsilon)$. Note that this limitation applies at the forward error correction (FEC) frame payload level, which includes frame PDU and frame CRC (if enabled). In other words, the current FEC coding rate has no impact on whether or not this limitation is met.

Similar resource request limitations were also introduced in [8] for multi-vendor interoperability purposes.

2.3.2. Capacity request signalling. In DVB-RCS2 volume-based CRs are expressed as 8-bit integers. Four scaling factors, 1x, 8x, 64x and 512x, are defined. DVB-RCS2 VBDC CRs are in units of bytes as opposed to slots, which is the convention adopted in the first generation of the standard [2]. Accordingly, NCC resource allocation algorithms of the first generation DVB-RCS, which expected VBDC requests in timeslots and allocated timeslots, will need to be modified to handle byte-based DVB-RCS2 VBDC requests.

Rate-based CRs in DVB-RCS2 are also expressed as 8-bit integers with 1x, 4x, 16x and 64x scaling factors and in units of kilobits per second.

Capacity requests can be encapsulated with other return link layer 2 signalling messages (e.g. ES-IS routing protocol dependency, logoff cause, mobility control etc.) in control PDUs. Control PDUs can be sent in timeslots for control payload and traffic-and-control payloads (tx_content_type: 2 or 3). Such timeslots may be available either for DA or RA. This is indicated in access_method field of FCT2 or TBTP (Figure 2).

3. ANALYTICAL ASSESSMENT OF THE DYNAMIC LOAD CONTROL IN DVB-RCS2

This section describes and evaluates (via numerical computation and simulations) an analytical model for the DVB-RCS2 load control algorithm behaviour. The RCST-side algorithm description can be found in Section 2.2.

3.1. Model description

Consider a system with n nodes (i.e. RCSTs) over an RA channel. Time is slotted, and each slot represents a transmission opportunity, namely, an SA slot or a CRDSA RA block. It is assumed that the NCC makes available a continuous sequence of transmission opportunities across consecutive superframes. In order to analyse the load control algorithm in isolation, it is assumed that the maximum rate limitation parameters are assigned suitably high values, so that an RCST can potentially exploit any transmission opportunity to send data over the RA channel, that is, max_consecutive_block_accessed = ∞ and min_idle_block = 0.

The traffic arrival process for each RCST is independent and is characterized by fixed-length packets queued in buffers of size Q. It is implicitly assumed that at most one unique payload is sent in each transmission opportunity (timeslot in SA and an RA block in CRDSA). Each packet fits in one timeslot, and the traffic generation model is specified by the probability distribution

$$q_k(T) = Pr\{k \text{ packets generated in an interval of } T \text{ slots}\},$$
$$k = \{0, 1, \dots, Q\}. \tag{1}$$

We define p_{tx} as the probability that an RCST sends a packet in a given timeslot.[6] Under these assumptions, the instantaneous load $g(t)$, that is, the overall number of concurrent transmissions

[6] p_{tx} is not (1-back_off_probability). p_{tx} depends on the probability of having data in transmission buffers and the current state of the load control algorithm (including back_off_timer state).

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performed over slot t, is described by a binomial random variable of parameters n and p_{tx}, and the average load on the RA channel can be expressed as

$$G = E[g(t)] = np_{tx} \tag{2}$$

The DVB-RCS2 normative load control mechanism aims to maintain the system run at a target operating point G^*, chosen to upper bound the packet loss probability over the RA channel. According to (2), the NCC may achieve this by either limiting the number of nodes using the RA channel or controlling their transmission probability, p_{tx}. While the former approach can easily be implemented but may not be desirable, tuning p_{tx} allows to accommodate RCSTs as needed, but is not straightforward, because the parameter stems from the load control settings as well as from the RCSTs traffic profiles. To derive this relationship, the Markov model presented in Figure 5 can be considered. The chain describes the load control algorithm state in a node. In Figure 5, p_b and M represent the back_off_probability and the back_off_time parameters, respectively, with the latter value being expressed in timeslots. The RCST starts in the idle state. At each slot, it may remain idle if no packets have been generated during the previous time period (probability q_0 (1) following the notation of (1)) or otherwise transition to a different state (probability $1 - q_0$ (1)). If k packets have been queued, the RCST may either have to refrain from accessing the medium for M slots, entering state b_k with probability $p_b\, q_k$ (1) or immediately proceed with potential transmissions, going to state tx_k with probability $(1 - p_b)\, q_k$ (1). While in b_k, the terminal continues the initial backoff with probability $(M - 1)/M$, which ensures the average permanence imposed by the back_off_time parameter. On the other hand,

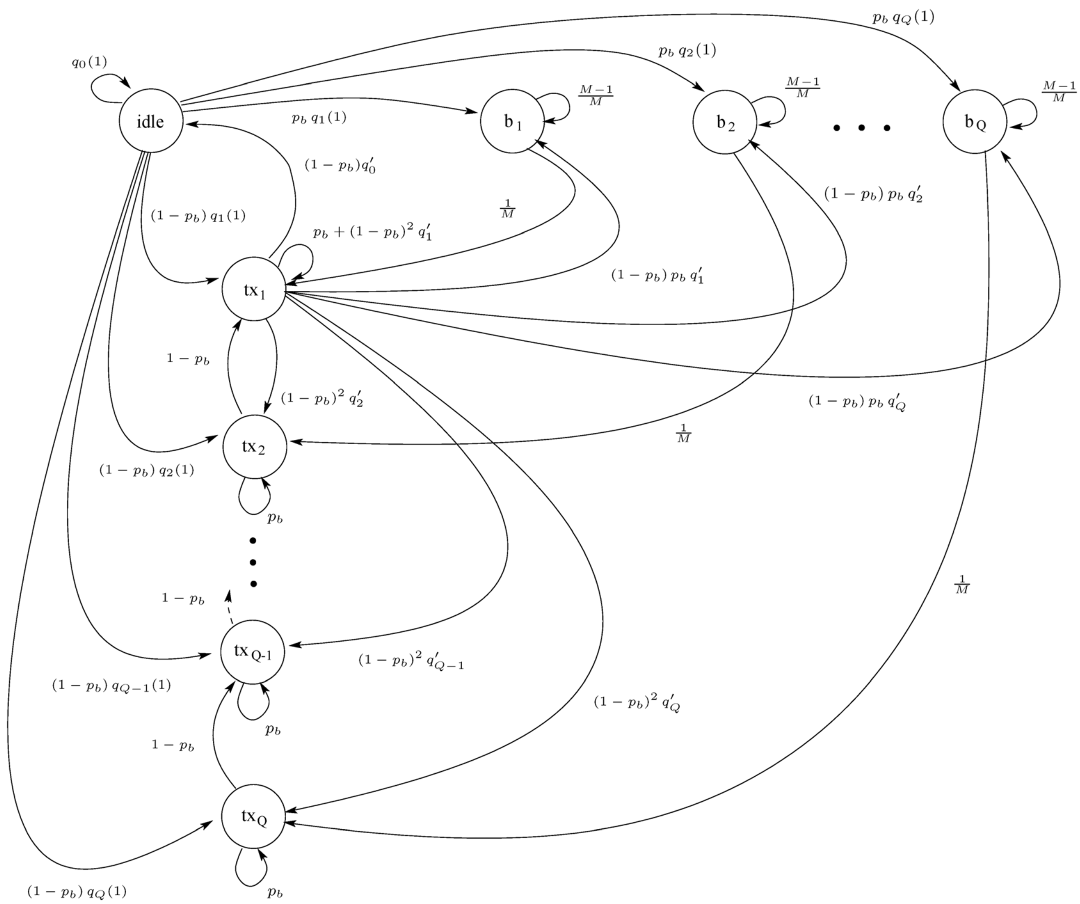

Figure 5. Markov chain model for the load control algorithm state of a node. State b_i indicates that the terminal has i packets to serve but is performing the initial backoff of M slots. Conversely, when in state tx_i, the node has i packets to serve and at each slot may transmit one of them with probability $1 - p_b$.

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a transition out of b_k can only be possible towards tx_k (probability $1/M$), because k packets have to be served. Suppose now to be in state tx_k, with $k > 1$. In this case, at each slot, the RCST can defer access to the RA channel (probability p_b) or transmit one packet and move to tx_{k-1} (probability $1 - p_b$), so that eventually tx_1 is reached, and the last packet is served.

When defining transitions from tx_1, it is important to consider that while the terminal was dealing with the current burst of data, other packets could have been generated and queued. In fact, while this effect may not play a key role for low arrival intensities, its contribution increases at higher traffic rates as well as for specific configurations of the system parameters p_b and M (e.g. very long initial backoffs or very high backoff probability). In order to account for this, assume for the moment that the size of the buffer when the RCST is ready to leave tx_1 follows a distribution q'_i, $i = 0,..,Q$, which will be derived later. Under this assumption, the RCST may return to idle only if the last packet of the current burst has been sent and no arrivals have taken place in the meanwhile, that is, with probability $(1 - p_b)\, q'_0$. Conversely, if k packets have been accumulated, the node may enter the initial backoff, moving to state b_k with probability $(1 - p_b)p_b\, q'_k$ or directly go to the transmission state tx_k with probability $(1 - p_b)^2\, q'_k$. Finally, no transition from tx_1 is performed if either the last packet is not sent in the current slot (p_b) or if it was sent, and a single packet has arrived while serving the current burst and will be processed without initial backoff ($(1 - p_b)^2\, q'_1$). The complete transition matrix P for the Markov chain, when the states are ordered as {idle, b_1, …, b_Q, tx_1, …, tx_Q}, is thus expressed as follows:

$$P = \begin{bmatrix} q_0(1) & q_1(1)p_b & q_2(1)p_b & q_3(1)p_b & \cdots & q_Q(1)p_b & q_1(1)(1-p_b) & q_2(1)(1-p_b) & q_3(1)(1-p_b) & \cdots & q_{Q-1}(1)(1-p_b) & q_Q(1)(1-p_b) \\ 0 & \frac{M-1}{M} & 0 & 0 & \cdots & 0 & \frac{1}{M} & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & \frac{M-1}{M} & 0 & \cdots & 0 & 0 & \frac{1}{M} & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & \frac{M-1}{M} & 0 & 0 & 0 & \cdots & 0 & \frac{1}{M} \\ q_0'(1-p_b) & q_1'p_b(1-p_b) & q_2'p_b(1-p_b) & q_3'p_b(1-p_b) & \cdots & q_Q'p_b(1-p_b) & p_b + q_1'(1-p_b)^2 & q_2'(1-p_b)^2 & q_3'(1-p_b)^2 & \cdots & q_{Q-1}'(1-p_b)^2 & q_Q'(1-p_b)^2 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 1-p_b & p_b & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 1-p_b & p_b & \cdots & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & \cdots & 1-p_b & p_b \end{bmatrix}$$

Two remarks of interest can be made. Firstly, it should be noticed that the model allows bursts of up to Q packets to be generated during the activity period. This corresponds to the working assumption of retrieving immediately the whole content of the queue, thus emptying it, when a burst starts to be processed, that is, when a transition either out of the idle state, or out of tx_1, or not directed to the idle state takes place. Secondly, packets that are generated while the RCST is not idle are not being immediately appended to the set of data units currently in process but rather have to wait for the current activity period to be over and may have to undergo an initial backoff period before being considered for transmission. This policy represents one of the possible implementations of the DVB-RCS2 load control algorithm and has been considered to prevent RCSTs from being stuck in too lengthy transmission cycles.

Under these assumptions, the transition probability matrix induced by Figure 5 makes it possible to derive the stationary distribution $\boldsymbol{\pi} = \{\pi_{\text{idle}}, \pi_{b\_1}, \ldots, \pi_{b\_Q}, \pi_{tx\_1}, \ldots, \pi_{tx\_Q}\}$ for the state of an RCST, obtaining:

$$\pi = \begin{cases} \pi_{tx\_1} = \dfrac{1}{(1-p_b)(\alpha + Mp_b) + \alpha A + A'} \\ \pi_{tx\_i} = \pi_{tx_1}\left(\alpha \sum\limits_{j=i}^{Q} q_j(1) + \sum\limits_{j=i}^{Q} q_j'\right) & i = 2, .., Q \\ \pi_{b\_i} = \pi_{tx\_1} M p_b (1-p_b)\left(\alpha q_i(1) + q_i'\right) & i = 1, \ldots, Q \\ \pi_{\text{idle}} = \pi_{tx\_1}\alpha(1-p_b) \end{cases}, \tag{3}$$

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where

$$.\begin{cases} \alpha = \dfrac{q_0(1)}{1-q_0^{'}} \\ A = E[q_i(1)] = \sum_{i=0}^{Q} i q_i(1) \\ A' = E\left[q_i^{'}\right] = \sum_{i=0}^{Q} i q_i^{'} \end{cases} \tag{4}$$

The computation of $\boldsymbol{\pi}$ requires a complete statistical specification of the size of the traffic buffer when the terminal has completed the service of a set of packets, that is, $q'_i, i=0, \ldots, Q$. In this perspective, it shall be noticed that the arrivals during an activity period intrinsically depend on the size of the traffic burst that was being dealt with. It follows that, for $i=0, \ldots, Q$:

$$q'_i = \sum_{j=1}^{Q} Pr\{i \text{ arrivals during burst service} | \text{served burst was of } j \text{ packets}) \\ Pr\{\text{served burst was of } j \text{ packets}\}. \tag{5}$$

The average service time for a set of j packets is given by:

$$T_j = Mp_b + \frac{j}{1-p_b}, \tag{6}$$

where the first addend accounts for the initial backoff of M slots undergone with probability p_b, while the second addend represents the mean time needed to transmit a certain number of packets under the geometric backoff. It follows from (1) that

$$Pr\left\{i \text{ arrivals during burst service} \middle| \text{served burst was of } j \text{ packets}\right\} = q_i\left(T_j\right). \tag{7}$$

As far as the conditioning term in (6) is concerned, the probability of having processed a burst of a certain size depends on whether the activity started from the idle state (i.e. the burst had been generated during a single slot) or from state tx_1 (i.e. the burst size followed q'_i itself). The former condition occurs with probability:

$$Pr\{\text{serving current burst from idle state}\} = \quad \beta = \frac{\pi_{\text{idle}}(1-q_0(1))}{\pi_{\text{idle}}(1-q_0(1)) + \pi_{tx_1}(1-p_b)\left(1-q_0^{'}\right)}, \tag{8}$$

while the latter is simply $Pr\{$ serving current burst served from $tx_1\} = 1-\beta$. Therefore, we obtain:

$$Pr\{\text{served burst was of } j \text{ packets}\} = \quad \beta \frac{q_j(1)}{1-q_0(1)} + (1-\beta)\frac{q'_j}{1-q'_0}, \tag{9}$$

where the normalization factors stem from the fact that we need to have at least one arrival to start a transmission activity. Combining (5)–(8), we finally obtain:

$$q'_i = \sum_{j=1}^{Q} q_i\left(T_j\right)\left(\beta\frac{q_j(1)}{1-q_0(1)} + (1-\beta)\frac{q'_j}{1-q'_0}\right).$$

This result suggests an iterative approach to numerically compute the stationary distribution $\boldsymbol{\pi}$. As a first step, we consider the set: $\{\beta^0, q'^0, \boldsymbol{\pi}^0\}$, where $\beta^0 = 1$; q'^0_i equals 1 for $i=0$ and is null otherwise, and $\boldsymbol{\pi}^0$ is the solution of the Markov chain found under the two former conditions. This corresponds to discarding packets that arrive while the RCST is not idle, so that the set of equations in (3) can be solved. Secondly, the value of β is updated using the set $\{\beta^0, q'^0, \boldsymbol{\pi}^0\}$, obtaining:

$$\beta^1 = \frac{\pi^0{}_{idle}(1-q_0(1))}{\pi^0{}_{idle}(1-q_0(1)) + \pi^0{}_{tx_1}(1-p_b)\left(1-q'^0_0\right)},$$

and the arrival distribution is subsequently refined in the form:

$$q'^1_i = \sum_{j=1}^{Q} q_i(T_j)\left(\beta^1 \frac{q_j(1)}{1-q_0(1)} + \left(1-\beta^1\right)\frac{q'^0_j}{1-q'^0_0}\right).$$

The iteration step is completed by solving the Markov chain as per (3) using q'^1, and the obtained state vector is labelled as $\boldsymbol{\pi}^1$. The whole process is then repeated until $\|\boldsymbol{\pi}^{\mathrm{m}} - \boldsymbol{\pi}^{\mathrm{m}-1}\|$ falls below a threshold that guarantees convergence up to a desired confidence.

The described procedure allows deriving the stationary distribution for the state of a node that obeys the medium access rules of the DVB-RCS2 load control algorithm when an initial backoff is present. On the other hand, the degenerate case, when $M = 0$, is of practical interest as a reference baseline. In order to obtain a statistical model that covers such a system configuration, the Markov chain discussed so far has to be slightly modified. In particular, when no initial backoff is considered, the states b_i do not appear, and the transition probability matrix P can be shown to become:

$$P = \begin{bmatrix} q_0(1) & q_1(1) & q_2(1) & q_3(1) & \cdots & q_{Q-1}(1) & q_Q(1) \\ (1-p_b)q'_0 & p_b + (1-p_b)q'_1 & (1-p_b)q'_2 & (1-p_b)q'_3 & \cdots & (1-p_b)q'_{Q-1} & (1-p_b)q'_Q \\ 0 & 1-p_b & p_b & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 1-p_b & p_b \end{bmatrix}$$

leading to the solution

$$\begin{cases} \pi_{tx\_1} = \dfrac{1}{\alpha(q_0 - p_b) + \alpha A + A' + q'_0} \\ \pi_{tx\_i} = \pi_{tx\_1}\left(\alpha \sum_{j=i}^{Q} q_j(1) + \sum_{j=i}^{Q} q'_j\right) \qquad i = 2, .., Q' \\ \pi_{idle} = \pi_{tx\_1}\alpha(1-p_b) \end{cases}$$

which can once again be numerically computed by means of the iterative approach discussed earlier in this section.

Once the stationary distribution for the Markov chain has been determined, it is finally possible to observe that an RCST accesses the RA channel in a given slot only if its state s belongs to the set $\{tx\}_{i}$, $i = 1,..,Q$, and if it chooses not to back off. Therefore, the transmission probability in (2) for the cases $M > 0$ and $M = 0$ is expressed, respectively, as:

$$p_{tx} = Pr\{s\epsilon\{tx\}_i\}(1-p_b) = \sum_{i=1}^{Q} \pi_{tx\_i}(1-p_b) = (1-p_b)\frac{\alpha A + A'}{(1-p_b)(Mp_b + \alpha) + \alpha A + A'} \; M > 0 \tag{10}$$

$$p_{tx} = Pr\{s\epsilon\{tx\}_i\}\;(1-p_b) = \sum_{i=1}^{Q} \pi_{tx\_i}(1-p_b) = (1-p_b)\frac{\alpha A + A'}{\alpha(q_0 - p_b) + \alpha A + A' + q'_0} \; M = 0$$

so that the average load on the RA channel when the normative dynamic load control algorithm is in place evaluates to:

$$G = n(1-p_b)\frac{\alpha A + A'}{(1-p_b)(Mp_b + \alpha) + \alpha A + A'} M > 0 \tag{11}$$

$$G = n(1-p_b)\frac{\alpha A + A'}{\alpha(q_0 - p_b) + \alpha A + A' + q'_0} M = 0$$

In conclusion, the presented analytical model provides a complete statistical description of the channel load and supports any packet generation model, as long as the distribution $q_i(T)$ is provided. In this perspective, the next section derives and discusses some results obtained assuming a specific bursty traffic model that can be of interest for the return link of a DVB-RCS2 system.

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3.2. Results under a Poisson–Pareto bursty traffic model

Let us consider, as a reference, a situation in which RCSTs generate traffic in the form of packet bursts. Burst arrivals are modelled according to a Poisson process of intensity λ (burst/slot/node), and each burst has a length of B bytes, where B is described as a Pareto random variable of parameters X_m and δ. The set of generated bytes are then split into $k = \lceil 8 \cdot \frac{B}{L} \rceil$ packets of L bits each, which are subsequently queued. Recalling the buffer size limitation Q discussed in Section 3.1, the probability distribution of the number of packets arrived within one burst can be determined as:

$$p(k) = Pr\{k \text{ packets generated in one burst}\} = \begin{cases} F(L/8) & k = 1 \\ F(kL/8) - F((k-1)L/8) & k \in [2, Q-1] \\ 1 - F((Q-1).L/8) & k = Q \\ 0 & k > Q \end{cases} \tag{12}$$

where $F(a)$ is the Pareto cumulative distribution function:

$$F(a) = \begin{cases} 0 & a < X_m \\ 1 - \left(\dfrac{X_m}{a}\right)^{\delta} & a \geq X_m \end{cases}$$

Under these assumptions, the probability distribution $q_k(T)$ needed to determine the stationary behaviour of a node is given by:

$$q_k(T) = \sum_{i=1}^{k} Pr\{k \text{ packets}|i \text{ bursts}\}\, Pr\{i \text{ burst arrivals in } T\} = \sum_{i=1}^{k} Pr\{y_i = k\} \frac{(\lambda T)^i e^{-\lambda T}}{i!}$$

where $y_i = \sum_{j=1}^{i} x_j$, and x_j are independent and identically distributed random variables distributed according to (12).

The probability mass function of y_i, in turn, can be computed by convolving i times $p(j)$ (12) with itself before properly truncating the achieved distribution to take into account the support constraint [0, Q] imposed by the finite buffer size. In order to exemplify the behaviour under consideration, Figure 6 reports, for different values of T, the distribution of the number of generated packets obtained

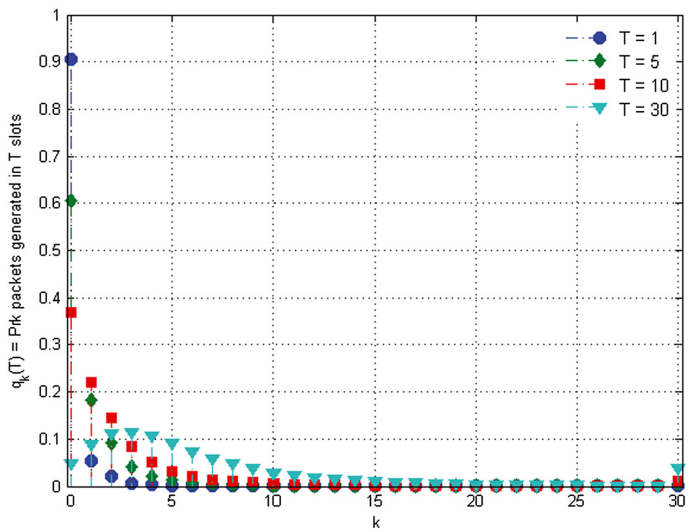

Figure 6. Probability mass function of the number of packets generated within a time period of T slots following the Poisson–Pareto traffic model under consideration. Different data sets represent different values of T. $\lambda = 0.1$ burst/slot/node, $L = 1500$ bit, $X_m = 81.5$ and $\delta = 1.1$.

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considering a queue capacity of 30 elements, a burst arrival intensity of 0.1 burst/slot/node, a packet length of 1500 bits and a burst size following the Web traffic model specified in [9], that is, $X_m = 81.5$, $\delta = 1.1$.

Once the traffic model has been specified, the load level on the RA channel can be determined as discussed in Section 3.1 for any set of backoff parameters $\{p_b, M\}$ of the DVB-RCS2 normative algorithm. In particular, observing that the average load is proportional to the number of nodes that have been allowed to send traffic over the channel (2), we introduce the normalized quantity $\gamma = G/n = p_{tx}$, which indicates the contribution that each RCST brings to the overall channel occupation. This value is particularly useful because it does not depend on the system cardinality but still encloses all the effects of the parameters of the load control algorithm on the channel utilization. Figure 7 shows the trend of γ against the backoff probability p_b under various configurations, while Q, L, X_m and δ have been fixed to 30, 1500, 81.5 and 1.1, respectively. In the plot, different line styles represent different arrival intensities: dotted curves are obtained for $\lambda = 0.05$ burst/slot/node, dashed curves for $\lambda = 0.1$ burst/slot/node and solid curves for $\lambda = 0.2$ burst/slot/node. On the other hand, different markers within one set of functions indicate different lengths M for the initial backoff, ranging from 0 to 50 slots.

All the curves present a similar behaviour, characterized by two different trends. In the first place, especially for low arrival intensities, there exists a region where the contribution γ of the single RCST to the average load is almost constant and does not depend on the $\{p_b, M\}$ set specified by the network controller. This describes the situation in which the number of arrivals during the activity period is negligible, and the terminal can process a complete burst prior to new traffic being generated. Under this condition, the average contribution of an RCST to the channel load is exactly A packet/slot, as expected and confirmed by the plot. The region of backoff probability values characterized by such a trend clearly reduces for larger arrival intensities λ and for longer initial backoffs M. On the other hand, sufficiently large values of p_b harness a terminal in longer backoff cycles and reduce its channel access rate, leading to the trends quantified in Figure 7.

As expected, it is also possible to notice that for any system configuration, the maximum value assumed by γ is never larger than the average number of packets generated per slot, that is, $\gamma \leq A$. This hints that new users can be admitted to an RA channel regardless of and without any modification to the $\{p_b, M\}$ set currently in use as long as $n < G^*/A$, G^* being the target average load on the medium. On the contrary, if n approaches or is larger than G^*/A, new RCST can be admitted without disrupting the desired operating point only by distributing updated and more stringent (i.e. larger p_b or larger M) backoff parameters.

Figure 7 also highlights how, regardless of the arrival intensity, for any feasible value of γ there always exists a configuration with $M = 0$ capable of achieving it. Such a result suggests that the average load on a RA channel can be controlled as effectively as with the normative algorithm by resorting to a simpler solution that only requires nodes to undergo an ALOHA-type contention over transmission opportunities and drops any initial backoff window. On the other hand, a non-null back_off_time

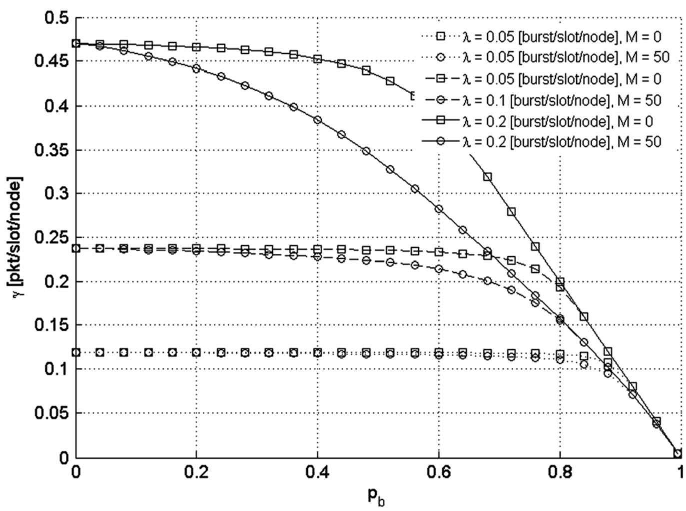

Figure 7. Normalized average load on the RA channel plotted against the backoff_probability (p_b) parameter.

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may be of use to induce a more condensed pattern for the access to the RA channel. From this viewpoint, in fact, when a system configuration $\{p_{b1}, M_1 = 0\}$ is in place, a node uniformly spreads on average its traffic on the medium over time. Conversely, an alternative set of parameters $\{p_{b2} < p_{b1}, M_2 > 0\}$ leading to the same overall channel load would enforce the terminal to transmit a burst of packets over a shorter time period, to then possibly refrain from occupying the channel for the whole duration of a backoff interval.

In order to verify the derived analytical solution and to evaluate the accuracy of the iterative approach that has been presented in Section 3.1, detailed simulations of a node behaviour following the normative DVB-RCS2 load control algorithm under the assumptions that characterized the discussed Markov chain have been carried out. In particular, the time evolution for the backoff state, buffer occupation and medium access over a Random Access Allocation Channel (RA-AC) have been tracked for a terminal generating traffic according to the Poisson–Pareto traffic model under consideration on a slot by slot basis. The outcome of this verification study, obtained by averaging the results of a sufficiently large set of simulations, is reported in terms of normalized average load γ in Figure 8 for a specific configuration ($\lambda = 0.05$ burst/slot/node, $M = 0$ and $M = 50$ slots). The trends shown here, together with other companion plots not reported because of space constraints, exhibit a very close match between analytical and simulative results, confirming the accuracy of the presented Markov chain for the whole range of backoff probability values.

The capability to predict the contribution of a single terminal to the overall load on an RA channel can be used to properly tune the system parameters to support a desired population size. Let us assume, for instance, that users characterized by a common traffic generation profile (specified by the parameters of the Poisson–Pareto distribution) have to share an RA channel where a target average load G^* shall not be exceeded. By applying the methodology discussed so far, the Markov chain model makes it possible to determine, for any initial backoff duration M, the minimum backoff probability p_b^* (i.e. the one minimizing the overall transmission latency) that allows to allocate n users while satisfying the overall constraint in the form:

$$p_b^* = \text{argmin}_{(pb)}[\lambda(M, p_b)], \qquad \text{subject to}, \lambda(p_b^*, M) \leq G^*/n.$$

Figure 9 illustrates the outcome of such a dimensioning for a target overall average load $G^* = 0.8$ packet/slot when $\lambda = $2e-4 burst/slot/node and for an average burst size of 4 kB ($X_m = 81.5$, $\delta = 1.02$, $L = 1500$). Assuming as reference an SA channel access and a timeslot of duration 100 µs (corresponding to a symbol rate of 4 Mbaud), the scenario describes a heavily loaded system with high traffic generation rate (5 burst/sec/node). Four possible values of the back_off_time are considered, namely, $M = \{$1e3, 5e3, 5e4, 1e5$\}$ slots, which is equivalent to $\{$100 ms, 500 ms, 5 sec, 10 sec$\}$. The plot clearly identifies two operating regions; on the other hand, for n lower than approximately 1300, a null backoff probability can be tolerated. This

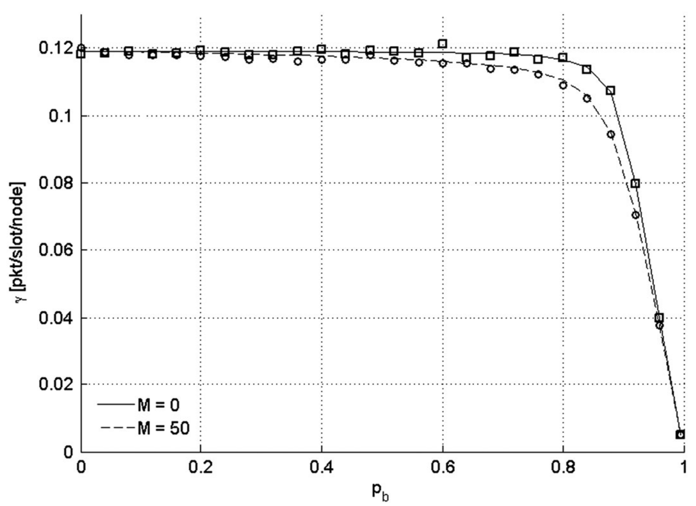

Figure 8. Normalized average load on the RA channel when the dynamic load control algorithm is employed plotted against the backoff_probability (p_b) parameter. Comparison of the results obtained via the analytical Markov chain (solid and dashed lines) with the results obtained via simulations (squared and circled markers). $\lambda = 0.05$ burst/slot/node, $M = 0$ and $M = 50$.

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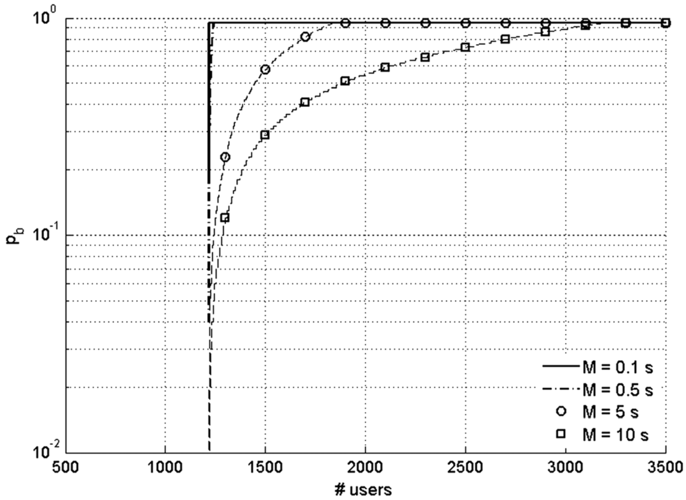

Figure 9. Minimum backoff probability value necessary to support a certain number of users over an RA channel without exceeding an average aggregate channel load $G^* = 0.8$ packet/slot. Different lines indicate different values of backoff_time. Traffic generation parameters have been set as $\lambda = 2\text{e-}4$ burst/slot/node, $\delta = 1.02$, $X_m = 81.5$ and $L = 1500$.

behaviour can be explained recalling that a single terminal generates on average A packet/slot. Therefore, as long as $nA < G^*$, users can be allocated on the RA-AC without any specific restriction, that is, following a classical SA approach and transmitting a packet as soon as it is generated, without violating the aggregate load constraint. Conversely, larger populations ($n > G^*/A$) can be supported only by resorting to increasingly high values of p_b. From this viewpoint, the figure also highlights how for small values of backoff_time, for example, $M = 0.1$ s, $M = 0.5$ s, a sharp transition between the two regions is present, so that more than G^*/A users can be admitted to the channel only if backoff probabilities very close to 1 are set. Such an effect can be mitigated if longer initial backoffs are considered, as prompted by the circle-marked and square-marked curves, reporting the behaviour of the system for values of M equal to 5 and 10 s, respectively.

As a final consideration, it is important to notice that the discussion carried out so far focused on how to tune the backoff parameters for the RA channel to operate around an average load G^*. In addition, it is also interesting to infer how stable the behaviour of the system is, that is, in terms of oscillations around the operating point, as well as to understand if the normative algorithm can be used to control this aspect. In this perspective, let us recall that the instantaneous load on the RA channel, under the set of hypotheses described in Section 3.1, is modelled by a binomial random variable of parameters n and p_{tx}. It follows that the load variance is given by:

$$\sigma_g^2 = \mathrm{Var}[g(t)] = np_{tx}(1 - p_{tx}) = G\left(1 - \frac{G}{n}\right) \tag{13}$$

Equation (13) shows that once a target average load G^* has been set, and the number of users in the system is fixed, the magnitude of the oscillations around the working point is uniquely determined. Therefore, with the normative algorithm proposed in DVB-RCS2, a coordinating unit can try to contain peaks on medium access only by either reducing the number n of users allowed to transmit on that RA channel or by moving the target average load to a lower value, reducing the channel utilization. Instead, it is not possible to reduce the load variance while keeping the same operating point by changing the backoff parameters. In other words, any set $\{p_b, M\}$ that leads to a given G also enforces the same value of σ_g^2.

3.3. Some remarks on CRDSA-based medium access with multiple unique payloads per RA block

The analytical model presented in Section 3.1 assumes that the RCST sends, at most, one unique payload per transmission opportunity. With SA, this assumption is certainly valid. However, with CRDSA, the RCST may send multiple unique payloads per transmission opportunity (as many as max_unique_payload_per_block). An accurate description of this feature by means of analytical tools,

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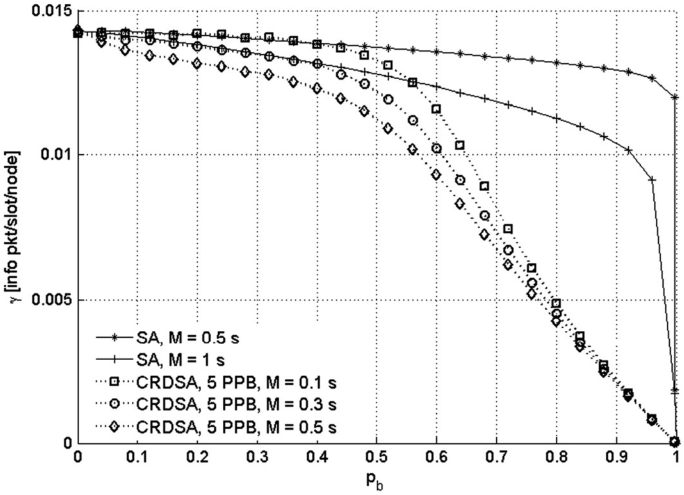

Figure 10. Normalized average load on the RA channel against the backoff_probability (p_b) parameter for SA (solid lines) and CRDSA (dashed lines). Different markers indicate different values of the initial backoff M.

though conceptually approachable, would significantly increase the complexity in terms of number of states and of possible transitions for the Markov chain model that was presented to track the behaviour of a terminal. We have therefore chosen to investigate the issue by extending the simulator discussed in Section 3.2 and by modifying the algorithms that characterized our analytical studies as follows.

When an RCST shall initiate a new transmission procedure, that is, when a new burst arrives while in idle state or when new traffic to be served is present once a burst has been completely served, an initial backoff of duration M transmission opportunities is undergone with probability p_b.

Once the potential preliminary waiting time has expired, each transmission opportunity, corresponding to a RA block, is selected for possible transmission with probability p_b or skipped with probability $1 - p_b$. When an RA block has been identified for access, the terminal considers the next packet of the burst currently being served and checks whether the max_number_of_unique_payload_per_block has been reached. If not, the payload is marked to be sent in the current RA block by means of CRDSA with probability p_b. The model assumes that the procedure is iterated for all the fragments of the frame until either max_number_of_unique_payload_per_block packets have been selected for transmission or the outcome for a fragment is not to proceed, that is, probability $1 - p_b$. Should one of these conditions be met before the burst is completely served, the terminal defers the transmission of the remaining packets to the next transmission opportunity that will be selected.[7]

We have tested this load control algorithm considering a system where an RA block spans over a whole superframe of 20 ms, composed of 50 slots of 400 μs each. The first set of results is shown in Figure 10, where the normalized average load over the RA channel (unique payloads per slot per node) is depicted against the backoff probability p_b. Solid lines report the behaviour of a SA-based system and are obtained analytically by means of the Markov chain model, whereas dashed lines describe CRDSA medium access with the max_number_of_unique_payload_per_block parameter set to 5. Different markers indicate different durations of the initial backoff (reported in seconds), while all the system configurations have been tested considering a buffer size of 30 packets and Poisson–Pareto bursty arrivals with $\lambda = 15$ burst/slot/node, $\delta = 1.1$, $X_m = 81.5$ and $L = 1500$.

The plot highlights how, for any value of p_b and under the same conditions in terms of initial backoff, the contribution of a terminal to the average channel load is lower when CRDSA is employed. This behaviour stems from two main factors. Firstly, with CRDSA, a transmission opportunity corresponds to a whole superframe. This implies that a terminal choosing not to access the medium in the

[7]This implementation of the load control mechanism implicitly assumes the min_idle_blocks parameter in the Lower Layer Service descriptor to be set to 0. This choice has been made in order to have results comparable to the ones obtained and discussed for SA-based medium access.

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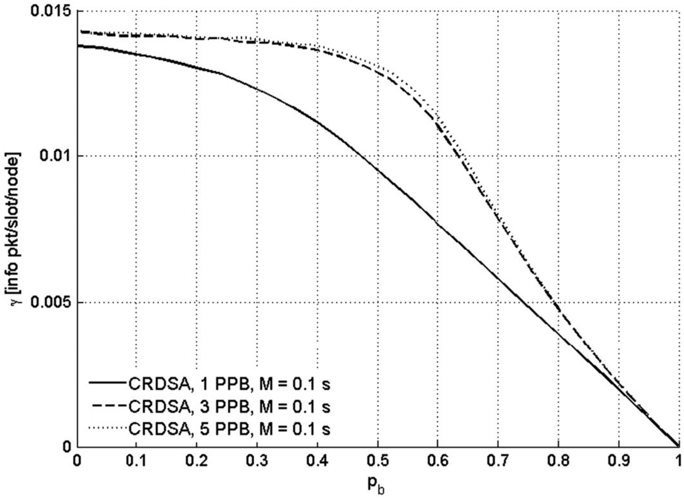

Figure 11. Normalized average load on the RA channel against the backoff_probability (p_b) parameter for CRDSA. Different line styles indicate different values of the max_number_of_unique_payload_per_block parameter. The initial backoff value has been set to $M = 0.1$ s. Traffic generation parameters have been set as $\lambda = 15$ burst/slot/node, $\delta = 1.1$, $X_m = 81.5$ and $L = 1500$.

current RA block skips multiple slots (e.g. 50 in our setup) but also that superframes marked for transmission can carry up to max_number_of_unique_payload_per_block packets (e.g. 5 in our setup) over several slots. Both factors reduce the average channel occupation for a given backoff probability with respect to SA, which instead perceives any timeslot as an opportunity to send a packet. Secondly, when CRDSA is used, an RCST actually transmits only if the current RA block is chosen (probability $1 - p_b$) and if the packet itself is marked for transmission (by means of an independent choice with probability $1 - p_b$ too). The latter condition is strictly related to the possibility of serving a variable number of payloads per RA block and does not hold for the basic SA scheme, as discussed in Section 3.1.

Further insights into the behaviour of the normative load control algorithm in combination with CRDSA are provided in Figure 11, which reports the normalized average load generated by an RCST for different values of the max_number_of_unique_payload_per_block parameter, ranging from 1 to 5.

In general, the plot confirms how larger values of max_number_of_unique_payload_per_block lead to a higher channel utilization for a terminal, as expected. Furthermore, it is possible to observe that enforcing a node to send at most one original payload per frame does not suffice to serve the overall generated traffic for the Poisson–Pareto profile under consideration even with the most aggressive policy, that is, no initial backoff and exploitation of each transmission opportunity with $p_b = 0$. The issue is instead already eased by allowing up to three packet transmissions per RA block. Figure 11 also shows how the curves obtained by setting max_number_of_unique_payload_per_block to 3 and 5 are rather close to each other for all the possible values of p_b. This result quantifies the intuitive conclusion that only a specific set of parameter values, related to the traffic to be served, can be used to effectively influence the average channel utilization of a terminal.

4. CONCLUSIONS

This paper provided a brief description of DVB-RCS2 user uplink access mechanism and proposed an analytical model for the RA load control algorithm. Several improvements have been introduced in DVB-RCS2 with respect to the first generation of the specification. This section provides a brief discussion on open issues that necessitate further investigation.

The DVB-RCS2 now supports adaptive coding and modulation on the return link. In addition, VBDC CRs are signalled in units of bytes. RA for user traffic, as well as signalling, is supported for both SA and the more advanced CRDSA. All these improvements call for a fresh look at the resource allocation mechanisms in DVB-RCS2—both at the RCST and the NCC sides.

There is room and need for more intelligent mechanisms that jointly use DAMA, RA and free capacity allocation. These mechanisms may now exploit higher degrees of freedom to provide differentiated service quality for a range of different applications (e.g. delay-constrained transactional applications, delay-tolerant bulk traffic etc.) while attaining higher throughput. Via joint use of RA and DA, thin-traffic transactional applications may enjoy low propagation delay of RA while heavy-traffic applications can exploit the high spectral efficiency of DA slots. Such mechanisms should also take into account and exploit the spatio-temporally-varying channel conditions across the RCST population.

The specification defines an RA load control algorithm, which is also analytically modelled in this paper. However, further investigation is needed for more advanced load control algorithms (especially at the NCC) that can achieve higher throughput and segregate between traffic sources with different QoS requirements. Resource management mechanisms may also be devised at a global level to dynamically allocate/release RA channels between overload and underloaded beams in the system.

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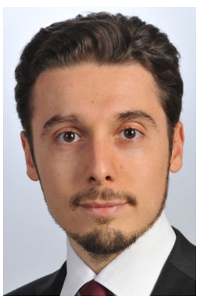

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