A Real Time Algorithm for Bandwidth and Time-slot Assignment for Rain Faded DVB-RCS Systems

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***Abstract*—Broadband satellite communication networks, operating at Ka band and above, play a vital role in today's worldwide telecommunication infrastructure. The problem, however, is that rain can be the most dominant impairment factor for radio propagation at these frequencies. This paper, addresses bandwidth and time-slot allocation problem for rain faded DVB-RCS satellite networks. We formulate the task as a combinatorial optimization problem and propose a novel algorithm for dynamic bandwidth and time allocation, which works with CRA type of traffic. The algorithm is evaluated using a MATLAB simulation with historical rain data for the UK.**

***Index Terms*—MF-TDMA, time-slot allocation, fade mitigation techniques, combinatorial optimization.**

I. Introduction

VSAT networks provide high-speed multimedia services, including voice, video and Internet for a vast number of subscribers distributed over a very wide area. The DVB-RCS stands for Digital Video Broadcast Return Channel via Satellite, which is a centralized communication system. There is a single station called Network Control Centre (NCC) that controls all communication processes in real time.

European DVB-RCS systems providers use the following access mechanisms recommended by the European Telecommunications Standards Institute (ETSI). TDMA is used on the forward link as the access mechanism, while the return link is shared by earth stations using an MF-TDMA scheme. Typically, Ku band (12-18 GHz) is used for the forward link and Ka band (18-30 GHz) for the return link [1]. Forward link transmissions for user terminals are organized in bursts. The bursts are assumed to be made of a fixed number of time-slots, which are long enough to transmit one fixed-size packet.

Satellite links can be affected severely by rain fading, which can reduce the link capacity. NCC has to make sure that extra time slots or extra bandwidth are available to provide users with the requested quality of service in varying weather conditions. Consequently, efficient Radio Resource Management (RRM) and bandwidth utilization under rainy conditions have become important research topics in satellite telecommunications.

Combinatorial optimization has been used to address the problem of efficient resource allocation in DVB-RCS satellite systems. In [2], resource allocation for rain faded forward links has been modeled as a knapsack problem. In this paper, we look into resource allocation for DVB-RCS return links. The difference is that here we have to work with MF-TDMA frames instead of TDMA.

The main contributions of this paper are as follows:

- We formulate the task of bandwidth allocation under rainy conditions mathematically as a combinatorial optimization problem.
- We propose a low-cost allocation algorithm to solve it. The main objective of the algorithm is to achieve a better bandwidth utilization while still meeting the Quality of Service (QoS) requirements.
- Finally, we evaluate the algorithm using a MATLAB simulation with real historical rain data for the UK.

The current version of the algorithm deals with the guaranteed throughput services. The guaranteed throughput services are defined as the services, which ensure that the subscriber always gets the bandwidth requested regardless of traffic behavior of other users [1].

The rest of the paper is structured as follows. Section II describes briefly the Bandwidth on Demand process and MF-TDMA frame. The allocation process is mathematically formulated as a combinatorial optimization problem. Section III describes the proposed allocation algorithm. Section IV presents the simulation scenario and results. Finally, section Vdiscusses directions for future work.

II. MF-TDMA frame and Bandwidth on Demand

The DVB-RCS NCC sends the general network information to Return Channel via Satellite Terminals (RCSTs) once the power is on. The NCC provides monitoring and control functions and generates the control and timing messages required for operating the satellite network. The messages are sent using Moving Picture Exported Group Transport Stream (MPEG-2TS) via the private data section, which is transmitted over the forward link. There are two types of forward links in the DVB-RCS specification: one for the interaction control and the second for data transmission. Both links can be supported by the same DVB-S transport multiplex [3].

MF-TDMA bandwidth portion is usually defined to be approximately 20 MHz due to the RCST maximum frequency hoping limitation [3][4]. The goal of the Bandwidth on Demand (BoD) process is to determine the resources required

Symbol	Definition
U	The total number of RCSTs supported by the network.
β	Buffer size (in packets) for a given RCST.
M	The total number of packets that can be buffered in the network, which is equal to the size of the RCST buffer multiplied by the total number of RCST supported by the network (all RCSTs have the same buffer size).
K	The number of available ACM modes in the network.
r_i	The rain fading level for RCST i.
N_k	The number of packets suffering rain fading of level k.
$f(x)$	The space required for a time slot with rain fading level of x in the MF-TDMA frame.
p_i	Number of time-slots requested by RCST i.
C	The available MF-TDMA space. The space here stand for a portion of bandwidth given for a duration of time in a single frame for data traffic.
B_k	The bandwidth assigned by BoD to mitigate level k rain effects.
L	The number of available MF-TDMA frames.
T	The duration of an MF-TDMA time-slot.
R_i	Requested data rate by RCST i..

Table I
LIST OF SYMBOLS

to satisfy the rate requested by an RCST. A BoD controller receives RCST data requests, selects an appropriate Adaptive Coding and Modulation (ACM) to match their rain level, and calculates the required bandwidth. The Media Access Control (MAC) then decides whether to accept or reject the request based on a set of rules as explained in [3].

Network traffic can be characterized as a Markov-modulated continuous stream of bits with peak and mean rates. On-off traffic sources with variable bit rates can be modeled as constant flow sources with an equivalent bandwidth [5]. Thus, we work under a simplifying assumption that the network uses the Constant Rate Allocation (CRA) to eliminate traffic complexity from the analysis. Consequently, the real-time bandwidth allocation will be governed purely by rain fading. There are several approaches to determining the equivalent bandwidth for the CRA. The fluid flow approach has been well investigated in [1][5][6]and[7]. In this paper, we use the normal "Gaussian" distribution investigated in [1-8].

III. Time Allocation Problem

A. Mathematical Formulation

The problem of resource allocation with rain fading can be defined as a combinatorial optimization problem. The goal is to pack optimally packets of different sizes into the MF-TDMA frame space. Table 1 describes the initial parameters for the optimization process.

At any time instant, let us define vector $\mathbf{p}$, as

$$\mathbf{p} = (p_i, ..., p_u \mid p_i \leq \beta \, , \, i = 1, 2, ..., U), \tag{1}$$

where p_i is the number of packets buffered by RCST i, which is always smaller or equal to the RCST buffer size for all stations. Similarly, vector$\mathbf{r}$ containing the instantaneous rain fading levels for all RCSTs is defined as

$$\mathbf{r} = (r_i, ..., r_u \mid r_i \leq K \, , \, i = 1, 2, ..., U), \tag{2}$$

where r_i is the rain fading level for RCST i. There can be many constraints involved in determining how to pack a given set of time-slots, and there are many objectives to be met, such as fairness, efficiency, QoS, and utilization. In this paper, the main objective is to transmit the packets using the smallest possible portion of the available MF-TDMA frame space. This problem can be described as follows:

$$maximize \ \frac{\sum_{i=1}^{U} \left(f(r_i) \cdot \sum_{j=1}^{p_i} x_{ij} \right)}{C \cdot L} \tag{3}$$

$$s.t. \ \sum_{j=1}^{p_i} x_{ij} = R_i \cdot \frac{T}{bits\, per\, slot}, \ \forall i \tag{4}$$

$$where, \ x_{ij} = \begin{cases} 1, if\ the\ packet\ is\ selected. \\ 0, otherwise. \end{cases} \tag{5}$$

The last constraint essentially specifies that each RCST should be able to transmit the requested number of packets within L MF-TDMA frames.

The secondary objective is to minimize the variation in the delays experienced by individual packets, also known as cell delay variation (CDV) [1].

B. The Algorithm

In any given time interval, there is a number of packets suffering K or less levels of rain fading, which are needed to be fitted into L consecutive MF-TDMA frames of capacity c each. For our algorithm, the total demand can be characterized as a $M \times K$ matrix W defined as follows:

$$w_{mk} \in \begin{cases} 1, if\ k{=}r_i, and\ m\ mod(i{*}\beta) \leqslant p_i. \\ 0, otherwise. \end{cases} \tag{6}$$

Each column corresponds to a different level of rain fading k. Each row corresponds to the packet sequence number in an RCST buffer. Packets from RCST 1 correspond to rows $1, 2, ..., \beta$, packets from RCST 2 correspond to rows $\beta+1, \beta+2, ..., 2\beta$. Packets from RCST$i$ correspond to rows $(i-1)\cdot\beta+1, (i-1)\cdot\beta+2, ..., 2(i-1)\cdot\beta$. Therefore, if RCST i suffers rain fading level of k, then the corresponding rows in column k of the demand matrix will be equal to 1, otherwise they will be equal to 0. The total number of '1's in each column of the demand matrix is equal to N_k and each row contains at most single '1'. Figure 2 illustrates this idea. The demand matrix can be used by the MAC to perform fitting of packets into MF-TDMA frames.

The main idea behind the proposed algorithm is to bundle together packets coming from RCSTs with the same rain fading level (the same ACM mode). This can be done by allocating carriers in MF-TDMA frame separately for each column in the demand matrix according to the actual number of packets in that column. The algorithm is specified in Figure 1.

The constraint in equation 7 is to ensure not to exceed the total frame bandwidth, where B_k defined as the bandwidth assigned by the BoD to mitigate level k rain effects. The packing procedure tries to reduce the CDV without violating any agreed QoS bounds. To achieve this, the procedure schedules

Step 1 (Initialization)
Create the demand matrix W
Step 2 (Iteration)
for $k = 1 \ldots K$ (processing each demand matrix column separately)
Calculate the required number of carriersC_k:

$$C_k = \left\lceil \frac{\sum_{m=1}^{M} w_{mk}}{(number\ of\ time\ slots\ per\ carrier) \cdot L} \right\rceil$$

$$C_k = \left\lceil \frac{N_k}{10 \cdot L} \right\rceil$$

$$s.t.\ C_k \cdot B_k \leq available\ bandwidth \tag{7}$$

Pack packets from column k of the demand matrix into the C_k carriers of bandwidth B_k.
Update available bandwidth (reduce by $C_k \cdot B_k$).
end for
Step 3
Delete W

Figure 1. Allocation algorithm

packets from the RCST with the longest packet delay first. This ensures that the packets with earlier deadlines are scheduled into earlier time slots within the L-frame window. Scheduling packets from RCSTs with the same rain fading level into of carriers of the same bandwidth reduces the amount of unused space in each MF-TDMA frame.

There may still be a situation when a portion of a carrier in a frame is unused because there are not enough packets at the given rain fading level to fill in all the time slot in that carrier. In the proposed algorithm, we introduce a time window to further improve carrier utilization. The time window is defined as the time interval required to transmit L MF-TDMA frames. Within this time period, requests will be stored in RCSTs buffers to be transmitted in the next time window. The algorithm looks at requests after each window. Therefore, instead of generating a Terminal Burst Time Plan (TBTP) for each super frame, there will be one TBTP generated for each time window.

Having the time window helps capturing more packets at a given rain fading level, which can then be transmitted within the carrier of an appropriate bandwidth. This means that less frames may be required to transmit them. The freed up frames in a given time window can be used to carry traffic from users with best effort level of services. For example, instead of transmitting one packet per carrier in 10 frames, the 10 packets can be buffered and transmitted in the next time window within a single frame. That means we will not need to reserve bandwidth for this rain fading level in the other 9 frames, and freed up bandwidth will be available for other services. This improvement in bandwidth utilization comes at the price of an added delay, which can be given in the following formula:

$$delay\,bound = L \cdot frame\,duration \tag{8}$$

A downside of using this algorithm is that it will delay and queue data even for unfaded satellite links. One possible way to address it is to use a dynamic window size dependent on the rain fading conditions as well as burstiness of traffic. The algorithm can be illustrated graphically using Figure 2, which shows how traffic from different RCSTs is grouped according to their rain fading levels. Each group of packets then is sequentially scheduled by MAC into the corresponding carriers across the MF-TDMA frames in the time window.

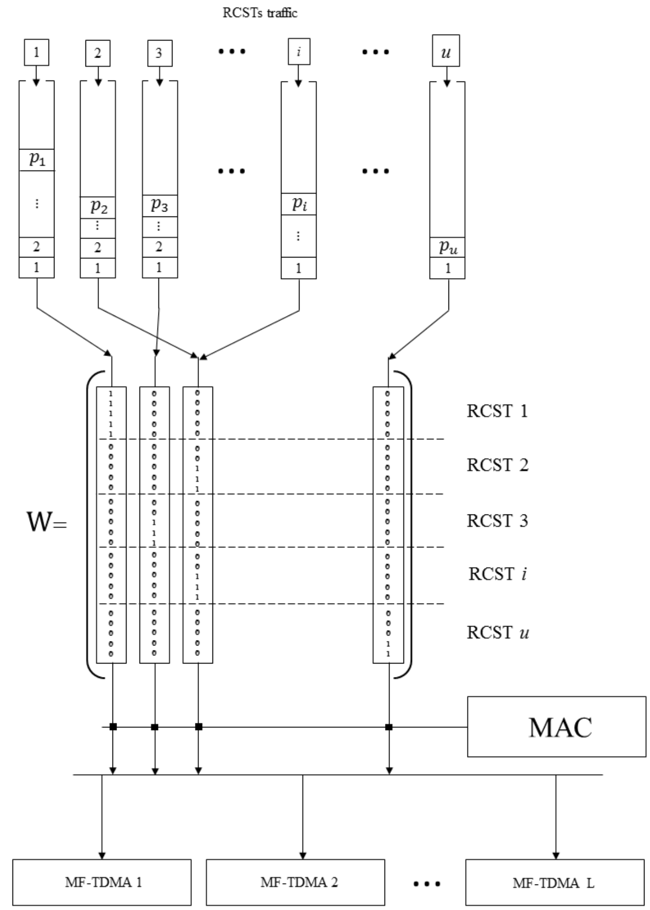

Figure 2. MAC serving K packets groups into L frames

IV. SIMULATION MODEL

The data rate that has been used is 144 Kb/s (topology A) guaranteed throughput of a low rate video streaming traffic type, with burstiness of 8. In the simulation, we assume the burstiness is measured over a single time window. More specifically, we assume that each RCST transmits at peak rate only for 1/8th of the time window duration. Thus, a total of 10 packets will be received in each time window. The MF-TDMA frame is be sub-divided in 60 standard carries with 10 time slots each, as shown in table 2 [8]. Each time slot has a capacity of 16 Kb/s guaranteed throughput. Therefore, 10 time slots per time window must be allocated to each RCST to satisfy the targeted rate. The above numbers were obtained from calculation carried in [8],[3], and [4]. In this version of the simulator, we considered one data type "video streaming" over one MF-TDMA of 20 MHz bandwidth, with transmission frequency of 20 GHz.

Peak information data rate	Slots per carrier and per frame				Carriers per frame
	traffic slots	CSC/ slots	SYNC/ slots	Total slots	
144 Kb/s	9	1	2	10	60
384 Kb/s	24	2	4	26	23
1024 Kb/s	64	4	8	68	9
2048 Kb/s	128	8	16	136	4

Table II
FEATURES OF THE MF-TDMA RETURN LINK

In the given simulation, 480 RCSTs were used with the following distribution pattern: 75% of the RCSTs were located in 4 different cities: London, Manchester, Dublin, and Glasgow, and the rest was randomly distributed all over the UK with the minimum separation distance of 1 km between RCSTs as illustrated in Figure 3.

The algorithm was applied on version 1 DVB-RCS system with 9 ACM FMT modes available, i.e., $K = 9$ in our case. The simulation uses historical rain data, with a simulation duration of 3 months (January, February and April 2011).

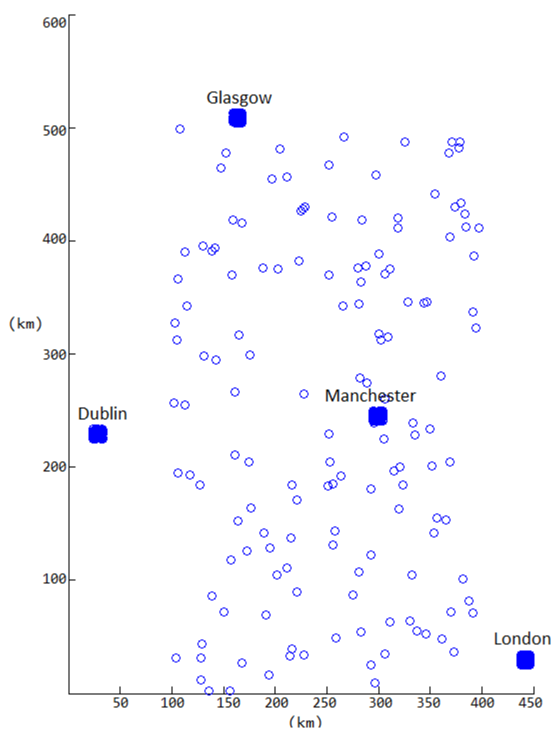

Figure 3. RCSTs ground distribution

A. Numerical Results and Performance Evaluation

Figure 4 shows the amount of used bandwidth for the given distribution of RCSTs. The bottom level of the used bandwidth corresponds to the minimum rain fading level (i.e. no rain). The overall bandwidth usage statistics can be represented as a CDF of total bandwidth used. This is shown in Figure 5.

As can be seen from the results shown in Figure 4 and 5, only up to 40% of the total allocated frame bandwidth was used at any moment in time. Moreover, for a standard 99.9% network availability only 35.2% of the frame bandwidth was actually used by the RCSTs.

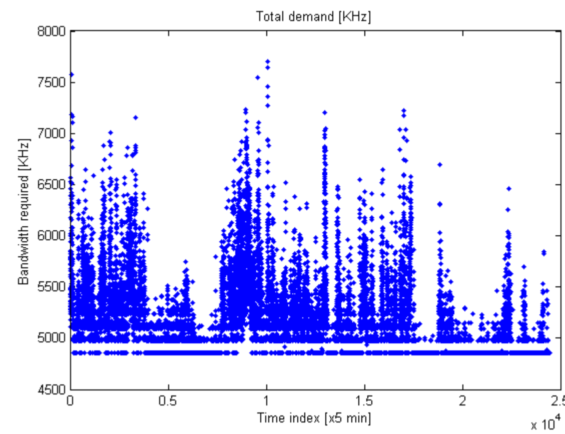

Figure 4. Total bandwidth used by the algorithm

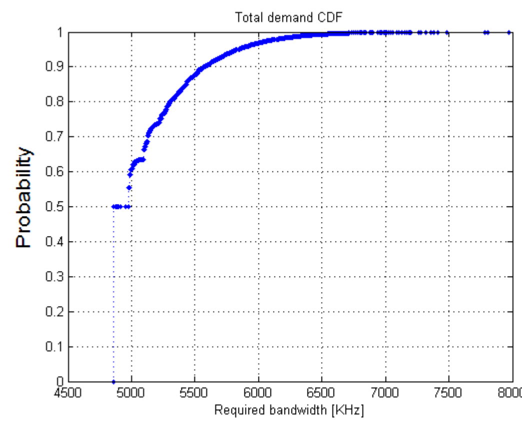

Figure 5. CDF for the total bandwidth used by the algorithm

V. CONCLUSION

The task of bandwidth and time slot assignment in rain faded DVB-RCS systems has been described and formulated mathematically as a combinatorial optimization problem. Unlike other referenced approaches, where RCSTs are divided into only two groups of rainy and non-rainy terminals, the proposed algorithm bundles traffic requests into multiple groups corresponding to their individual rain fading levels. The algorithm also uses a time window, which consists of multiple consecutive MF-TDMA frames, to improve time slot utilization within each carrier and free up frame bandwidth for other services. Our evaluation of this algorithm using a simulation with historical rain data shows a significant improvement in bandwidth utilization. Only 35.2 to 40% of the available frame bandwidth was used at any given time.

In the future work, we will be studying the effects of geographical distribution of RCSTs on the total demand. The current version of the algorithm can also be expanded to include different types of services and address the delay bound issue as one of the primary objectives.

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