

# CENTRALLY MANAGED MF-TDMA BROADBAND NETWORK WITH FADE MITIGATION BUILT UPON DVB-RCS

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## **Abstract**

*This paper proposes a methodology on how to design a centrally managed satellite network in the presence of rain fading as encountered on an actual spotbeam area whilst meeting the user-specified QoS requirements. A possible Fade Mitigation Technique applicable to DVB-RCS is described based on mechanisms supported by the Standard. The paper also presents the development of a novel space-time model of rain attenuation, suitable for application to the dimensioning and real-time management of Ka/V band broadband MF-TDMA networks.*

## **1 INTRODUCTION**

A result of the need to accommodate high-rate transmission is to push into increasingly higher frequency bands, namely Ka band (27-40 GHz) and V band (40-75 GHz). This trend is explained by the relatively large segments of frequency spectrum required for supporting the high data rates planned in newer systems, [1]. Most VSAT and Digital Broadcast Satellite TV systems in operation today use portions of the Ku band.

A major drawback to the use of higher frequencies is significant rain attenuation, as this increases rapidly with increasing microwave frequency, [2], [3], [4]. It can cause serious signal quality degradations of earth-space communication links and can therefore have a major impact not only on individual links, but on the whole network, which will be affected on a global basis.

MF-TDMA allows a group of Return Channel Satellite Terminals (RCSTs) to communicate with a Gateway using a set of carrier frequencies. In order to guarantee a Quality of Service, it is important that the NCC gets to know the actual needs of each of the active RCSTs of the network. Therefore each user station needs to monitor and measure its specific traffic requirements that are communicated to the NCC. If resources are available, the NCC will generate a new Terminal Burst Time Plan (TBTP) accommodating the needs of all its active stations at a superframe/frame level, [5].

## **2 BANDWIDTH ON DEMAND OVER MF-TDMA**

Most new generation Ka-band satellite systems are being designed to provide low-cost telecommunication services to hundreds of millions of users. In order to maximise the system capacity, frequencies can be allocated dynamically and reused many times. "Bandwidth on Demand" can be employed to support the maximum amount of users possible. On the billing side, bandwidth on demand enables users to pay only for the bandwidth they utilise, [6].

### **2.1 Segmentation of Return Link Capacity: A Simplified Scenario**

The timeslots of the return link are organised and numbered so that the network is able to allocate them to individual active RCSTs. Figure 1 shows how the global return link capacity may be segmented amongst a group of RCSTs; the network will then manage several superframe identifiers, SF\_IDs, (i.e. separate sets of carrier frequencies).

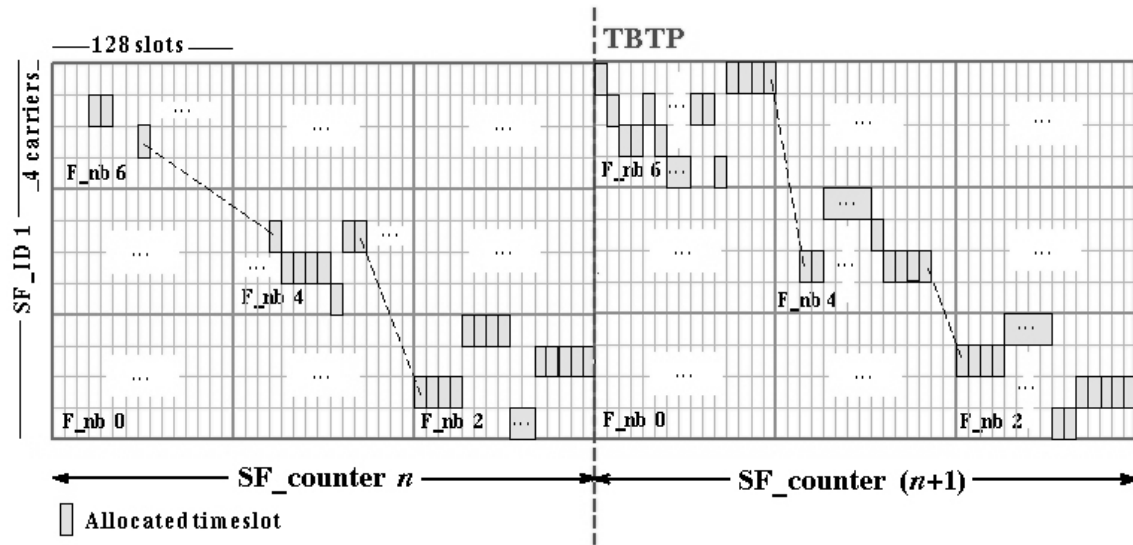


Figure 1. Capacity segmentation and timeslot allocation: an example

For simplicity reasons it is assumed that these frequency sets are fixed, i.e. superframes have a fixed bandwidth (otherwise a change in a superframe's bandwidth would affect the whole arrangement and all RCST groups would then have to be notified and have their superframe bandwidth adjusted appropriately (hence more signalling). For each superframe of a given SF\_ID, allocation of timeslots is communicated to the RCSTs via the Terminal Burst Time Plan table. An RCST is there on allowed to transmit data bursts in timeslots, which were allocated to it.

As shown in Figure 1, the consecutive superframes of a given SF\_ID are contiguous in time. Each occurrence of a superframe in time is labelled with a number called "SF\_counter". These two superframes of this particular SF\_ID 1 are of the same composition and duration, unless a notification that a change should be applied is provided; this can occur at the boundary between two superframes (between two consecutive SF\_counters of the SF\_ID), so that the next superframe is of different composition and/or duration. This notification involves the TBTP and the Superframe, Frame and Timeslot Composition Tables (SCT, FCT, TCT).

A superframe is composed of frames, themselves composed of timeslots. In a superframe, frames are numbered from 0 (lowest frequency, first in time) to  $N$  (highest frequency, last in time), ordered in time then in frequency, ( $F\_nb$  represents the frame number) and can take the values  $0 \leq N \leq 31$ . A frame is composed of timeslots. It may span over several carrier frequencies. In a frame, timeslots are numbered from 0 (lowest frequency, first in time) to  $M$  (highest frequency, last in time), ordered in time then in frequency. The number of slots in a frame can be in the range  $0 \leq M \leq 2047$ , [7].

Assuming that the bandwidth and duration of superframes, frames and timeslots is fixed, for an uplink burst rate of 2048 kbps, a typical MF-TDMA frame would last for 26.5 ms. The frame includes 4 carriers of 128 traffic slots each (i.e. 512 slots per frame), with rate granularity of 16 kbps (i.e. the minimum rate that can be achieved over the period of a frame by the allocation of just one timeslot).

Thanks to the system bandwidth-on-demand capability, a user station can vary the average bit rate according to its traffic needs by being allocated 1, 2, 3, ... up to  $M_c = 128$  slots/frame leading to 16, 32, 48, ... up to  $(M_c \times 16) = (128 \times 16) = 2048$  kbps over a frame duration.

Each terminal may transmit on any single frequency at a given time; it is not allowed to transmit data on more than one carrier at a time, in order to minimise the power output requirement and reduce the hardware complexity of terminals. The RCST will process the TBTP message received from the NCC, to extract the assignment count and timeslot allocations for its next uplink transmissions.

## 2.2 Satellite Access Control

The synchronisation burst and the optional prefix attached to ATM traffic bursts contain the Satellite Access Control field composed of signalling information added by the RCSTs for the purpose of requesting capacity for the session. The Request sub-field within the SAC accommodates capacity requests signalled from the terminal in terms of uplink payload slots required (either fixed or variable number of slots in each frame, or even total number of uplink payload slots required to empty its queue). Upon receiving the capacity request messages, the NCC generates a TBTP table and sends it, so that each RCST knows what timeslots have been assigned to it. This mechanism can also be used to drive a fade mitigation technique, i.e. for the purposes of FMT slot reservation when a terminal needs more resources under rain conditions.

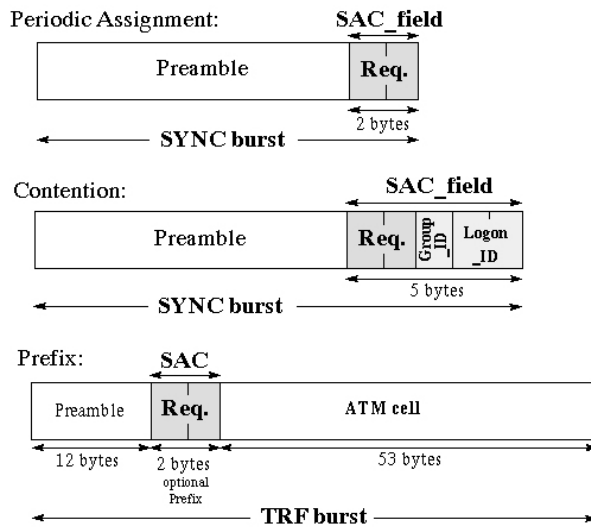
### 2.2.1 Mini-slot Out-of-Band Request (OBR)

#### (i) Periodic Assignment Based OBR

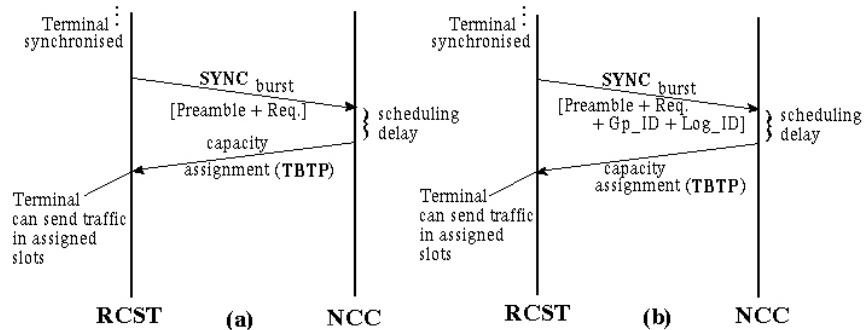
This mechanism is based on a periodic assignment to logged-on RCSTs of bursts smaller than traffic timeslots. It carries control and management information from the RCSTs to the NCC and is also used for maintaining RCST synchronisation. This mechanism is supported by the SAC Request sub-field used in synchronisation bursts.

#### (ii) Contention Based OBR

In this case, the mini-slot can be accessed by a group of RCSTs on a contention basis. This mechanism is supported by the Satellite Access Control Request, Group\_ID and Logon\_ID sub-fields used in the synchronisation bursts (see Figures 2 and 3).



**Figure 2.** Examples of SAC field composition (a) SYNC mini-slot (b) contention based SYNC mini-slot (c) TRF prefix method



**Figure 3.** Signalling regarding OBR for capacity through (a) periodically assigned SYNC mini-slot (b) contention based SYNC mini-slot

### 2.2.2 Prefix Method or In-Band Request (IBR)

This method is based on an optional prefix attached to ATM traffic bursts. If used, the prefix carries control and management information from the RCSTs to the NCC. This mechanism is supported by the SAC Request sub-field when appended to ATM traffic bursts (see Figures 2 and 4). Obviously the use of IBR signalling allows for the reduction in the traffic load over

the reservation channels, which are normally randomly accessed by terminals to contend for bandwidth. IBR has in fact the great advantage of being collision-free. Hence a terminal that has been assigned traffic slot(s) should use IBR (also known as “piggy-backed” requests). In this way, the out-of-band request slots can be shared by terminals that do not have any assigned traffic slot. The waiting time to send a reservation will also be reduced due to the availability of both IBR and OBR slots, [8].

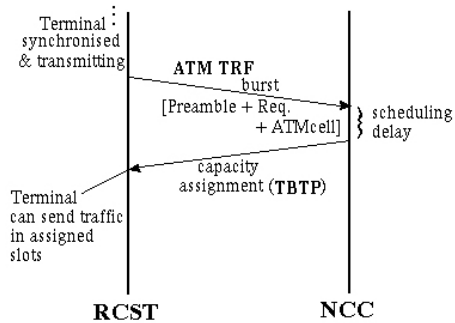


Figure 4. Signalling regarding IBR for capacity through TRF prefix method

### 3 BASIS FOR IMPLEMENTATION OF A FADE MITIGATION TECHNIQUE

#### 3.1 Forward Link Signalling (FSL) supporting a Fade Countermeasure

The TCT defines parameters concerning the coding for error protection; two coding schemes are supported, Turbo and concatenated coding (outer code: Reed-Solomon, inner code Convolutional).

All sections of the SCT, FCT, TCT, and broadcast Terminal Information Message (TIM) will be transmitted at least every 10 s. This implies that the coding parameters (defined in the TCT) can be updated at least every 10 s; this is of great interest, as in the case of rain, changing the coding or symbol rate is actually a fade countermeasure.

The repetition rate can take any value equal to or greater than 1/(10 sec), i.e. these tables can be retransmitted asynchronously as frequently as required, and this can occur at any time during a superframe; only in the case when the inverse of this rate is equal to the superframe duration, the tables will be transmitted synchronously at the exact beginning of every superframe.

In addition, the TIM will be updated as required to reflect system status changes requiring immediate notification of the RCSTs. For example, the transmission of the TIM table with its RCST\_status field set to "00000010" (Rain\_Fade\_detect bit set to '1') would indicate that the NCC is performing a reconfiguration procedure (e.g. increasing the code rate) to establish rain fade settings. Similarly, a "00000100" (Rain\_Fade\_release bit set to '1') would mean that the NCC is restoring settings due to cessation of a rain fade event, [7].

In the context of FMTs, one can foresee two basic scenarios. In the first scenario, each RCST monitors the channel conditions (in terms of rain attenuation). Based on the detected conditions, the RCST issues a set of new QoS requirements that not only cover its actual traffic needs but also its FMT needs. Thus each RCST would “lie” to the NCC and ask for more resources to accommodate its FMT needs. Here the already built-in reservation mechanisms described above (see Figure 2) can be used for the purposes of FMT slot reservation.

A second approach relies on the monitoring of the whole satellite footprint (using for example a weather radar network) so that, at any time, the NCC has an image of the rain conditions over the whole network. The allocation of timeslots is performed by the NCC from the true traffic and QoS requests of all the RCSTs. The FMT allocation is done independently by the NCC that takes into account the measured rain conditions, [5]. Both methods do not require any additional specific signalling. They are therefore efficient in terms of spectrum utilisation.

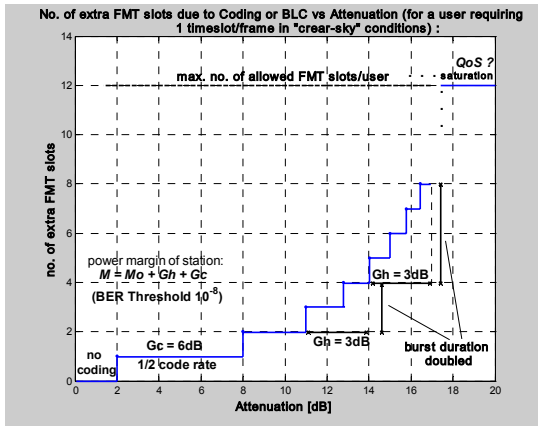
#### 3.2 Coding and Burst Length Control (BLC)

Within an adaptive MF-TDMA fade countermeasure scheme a portion of MF-TDMA timeslots is reserved as a shared resource, which can be distributed to any stations within the network that are subject to rain fading. When a burst within the MF-TDMA frame is subject to fading, it is allocated some extra timeslots into which it can expand. Since the user data rate is not changed this expansion results to an increase in average power (or energy/bit) of the signal and so counteracts the effect of the fade, [9].

If  $G_C$  is the coding gain obtainable by coding the message, and the burst duration is increased  $H$  times (i.e. the station is allocated  $H$  extra FMT timeslots), then the original power margin,  $M_0$ , of the station is increased to, [10]:

$$M = M_0 + G_H + G_C = M_0 + 10 \log_{10} H + G_C \quad (1)$$

Every time the burst duration is doubled in time, there is an increase in average transmitted power of 3 dB. Figure 6 illustrates an example of employing coding and bit rate reduction to counteract fading. Switching from no coding to 1/2 coding rate provides a 6 dB increase for a BER threshold of  $10^{-8}$  (see Figure 5). In general, if  $N$  is the original number of slots/frame



**Figure 6.** No. of extra FMT slots due to coding or BLC vs. attenuation protection

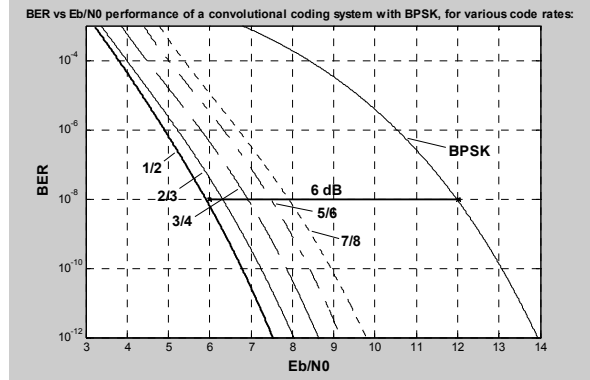
then the total number of slots required would be  $(7/8)/(1/2) \times 1 = 1.75 \approx 2$  slots, i.e. one extra timeslot to fit the coded bits. For a BER objective of  $10^{-8}$  (see Figure 5) this would translate to an extra 2 dB protection against fading. If, on top of this, bit rate reduction (or burst length control) was employed, an additional 3 dB protection (total of 5 dB) would be provided by transmitting the information bits at a speed that is twice as slow, i.e. over twice as many slots:  $(r_1/r_2) \times N \times 2 = 3.5 \approx 4$  slots, i.e. 3 extra timeslots in total.

### 3.3 Linking BER to QoS Performance Parameters

It should be noted, however, that, for new Ka-band systems, the  $C/N_0$  loss due to attenuation does not correspond directly to the degradation of the QoS offered to the end-user, because of a complexity in system architectures and a large variety of multimedia applications. To achieve a good assessment of this QoS information, the parameters derived by propagation models are not sufficient and estimating the distributions of more oriented QoS parameters is required. These parameters (Cell Loss Ratio and other ATM performance parameters) can be directly derived from the physical layer main parameter BER, [11]. The equations for the conversion from the BER into the ITU-T Rec. I.356 parameters, [12], depend on the error pattern model (random or burst errors) and rely on the principle of the Header Error Control mechanism implemented in ATM systems.

### 3.4 Dimensioning and Management of the FMT Resource at a Network Level

In the event of rain in some portion of the footprint (see Figure 7), the drop in QoS on individual links will require the allocation of spare timeslots to counteract for rain attenuation.



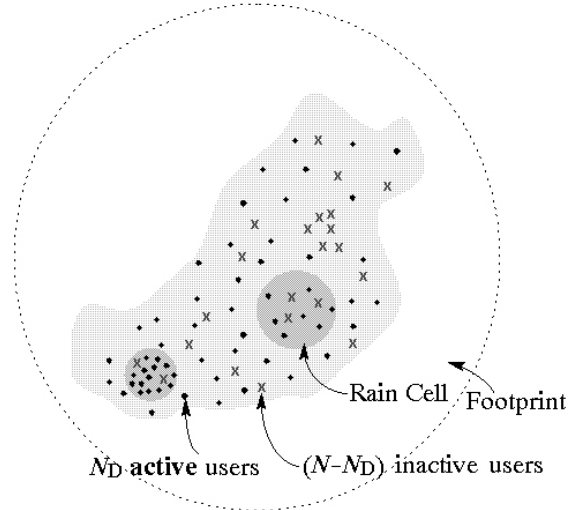
**Figure 5.** BER vs.  $E_b/N_0$  performance of a Convolutional coding system with BPSK, for various code rates

being transmitted, reducing the code rate from the baseline code rate  $r_1$ —decided by the clear-sky link budget and the QoS (BER) objective—to a new code rate  $r_2$ , results in expanding the transmission over  $(r_1/r_2) \times N$  timeslots. For example, if one slot was originally used and the code rate switched from a baseline clear-sky code rate  $r_1 = 7/8$  to a lower rate  $r_2 = 1/2$  to combat fading,

Assuming a population of  $N$  users, the NCC must be able to learn quickly about the links affected, so that allocation of communication and FMT slots can be achieved. As explained above, service communication can be achieved through OBR and IBR requests.

A major issue is that the MF-TDMA should be able to support the active users. This implies that if the number of FMT spare slots is limited, there will be a finite blocking probability of not meeting QoS parameters originally agreed. Alternatively, the requests may be queued, in which case, the limited capacity in the presence of rain will result in longer delays or a re-negotiation of QoS between RCST and NCC could be performed depending on the service agreement.

Figure 7 shows an example of rain cells over areas with active and non-active users inside the coverage area of a satellite. It becomes apparent that the total number of required FMT slots depends on: (i) users' density and location (the greater the concentration of users the greater the number of required FMT slots); (ii) space and time characteristics of rain (for rain over large areas, more FMT slots are required); (iii) magnitude of the rain attenuation; (iv) actual traffic characteristics of the user stations; (v) QoS parameters.



**Figure 7.** Example of rain cells over areas with active and non-active users inside the footprint of a satellite

Furthermore, depending on the hour of the day or the month, the rain conditions may be quite severe resulting in a much more extensive use of FMT slots. This would get even worse if worst fades occur at times when user traffic is high.

We therefore conclude that the design of MF-TDMA networks with burst-length control requires a detailed study of the impact of rain attenuation on the satellite footprint. Long-term analysis will allow investigating the share between traffic and FMT slots whilst short-term analysis will permit to study the resource allocation algorithms that the NCC needs to run for a rapidly converging and fair management of the MF-TDMA channel.

#### 4 SPACE-TIME MODEL OF RAIN ATTENUATION

The performance of FMT resource allocation algorithms described in the previous section needs to be evaluated in a network simulator. Such a simulator would need a fine scale simulation of the rain attenuation conditions encountered on a satellite footprint. Recent propagation activity has focused on the space-time modelling of rain fields.

A rain attenuation field can be simulated in space and time using a mixture of time and frequency domain signal processing. Such rainfield model can be used to simulate the variations of CNR over the whole footprint. It can consider seasonal/diurnal variations of rain for realistic worst-month and time-of-the-day dependent rain conditions.

The proposed model simulates rain attenuation on a  $(x_1, x_2)$  grid representing the  $N^2$  locations of interest for the network simulation. It is assumed that it rains on average only a fraction  $f(x_1, x_2)$  of the time at any location. When it rains, the attenuation is log-normally distributed with two location dependent parameters  $m(x_1, x_2)$  and  $\sigma(x_1, x_2)$ , which can be easily determined from the ITU-R rain model. These parameters can also encompass diurnal, monthly or seasonal variations, if they are fitted to CCDFs of diurnal, monthly or seasonal rain attenuation. The attenuation field can be synthesised using the non-linear transformation:

$$A(x_1, x_2) = \begin{cases} 0, & \text{if } g(x_1, x_2) < g_0 \\ \exp(m(x_1, x_2) + \sigma(x_1, x_2) \otimes g(x_1, x_2)), & \text{otherwise} \end{cases} \quad (2)$$

Here  $g(x_1, x_2)$  is a 2D Gaussian field with unit variance and zero mean. Whenever  $g(x_1, x_2) \geq g_0 = Q^{-1}(f)$ , it is raining. Thus  $g(x_1, x_2)$  can be transformed to a

lognormal variable using an exponential (array) transformation. This can be achieved by generating a complex field,  $a(k_1, k_2)$ , and then taking the inverse Fourier transform:

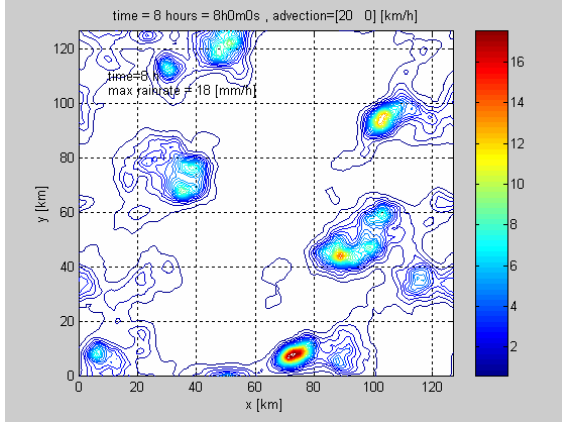
$$g(x, y) = \sum_{k_1=0}^N \sum_{k_2=0}^N a(k_1, k_2) \exp\left(\frac{i2\pi}{N}(k_1x + k_2y)\right) = IFT2\{a(k_1, k_2)\} \quad (3)$$

To get a good field  $g(x_1, x_2)$ , we need to consider the spatial cross-correlation function  $c_g(d)$  of rain where  $d \equiv |\vec{x} - \vec{y}|$  is the distance between two geographical points  $\vec{x} = (x_1, x_2)$  and  $\vec{y} = (y_1, y_2)$  of interest. Whilst for short distances the form  $c_g(d) = \exp(-d/5 \text{ km})$  is a reasonable model for modelling site diversity in UK, [13], [14], a correlation function considering meso- or synoptic ranges for Italy takes the double exponential form:  $c_g(d) = 0.94 \exp(-d/30 \text{ km}) + 0.06 \exp^2(-d/100 \text{ km})$ . An alternative approach is to analyse radar data and produce the spectrum of the log of rainfall rate, which is the Fourier transform of the cross-correlation function. Once a suitable correlation function has been chosen, we can calculate its Fourier transform:

$$C_g(k_1, k_2) = \sum_{x_1=0}^N \sum_{x_2=0}^N c_g(x_1, x_2) \exp\left(-\frac{i2\pi}{N}(k_1x_1 + k_2x_2)\right) = FT2\{c_g(x_1, x_2)\} \quad (4)$$

The complex random field can be obtained by filtering complex 2D noise (zero mean, unit variance)  $n(k_1, k_2)$ , which in the Fourier domain is a simple multiplication:

$$a(k_1, k_2) = C_g(k_1, k_2) \otimes n(k_1, k_2) \quad (5)$$



The model (2) to (5) only generates a single (original) map of the rainfield. A typical output is shown in Figure 8.

It is also important to add two realistic features to simulate time-dependent effects. For this the original rainfield is modified within a “for loop” simulating the passage of time. The first modification is the advection of the rainfall attenuation field. Assuming a velocity  $\vec{V} = [V_1 \ V_2]$  m/s in the  $(x_1, x_2)$  plane, the translated rainfield a short time  $t$  later is obtained using:

**Figure 8.** Typical output of the rainfield simulator

$$g(x_1 - V_1t, x_2 - V_2t) = IFT2\{a(k_1, k_2) \otimes \exp[-it(k_1V_1 + k_2V_2)]\} \quad (6)$$

The second modification takes into consideration the fact that rain effects have random temporal variations related to the natural birth and decay of rain cells over the field. It is well accepted that rain attenuation shows first order spectrum characteristics. One simple way of implementing this is to make  $g(x_1, x_2)$  an auto-regressive temporal process that can be synthesised using the following difference equation:

$$a_{\text{new}}(k_1, k_2) = \exp(-\beta t) \otimes a_{\text{old}}(k_1, k_2) + \sqrt{1 - \exp(-\beta t)^2} \otimes n_2(k_1, k_2) \quad (7)$$

where  $n_2(k_1, k_2)$  is complex noise with zero mean and unit variance (uncorrelated with the one in equation (5)). The constant  $\beta$  [1/s] defines the temporal characteristics of rain attenuation and has been estimated from experimental data in [5], [13], [14].

## 5 CONCLUSIONS AND FUTURE WORK

This paper has presented a review of Bandwidth on Demand for MF-TDMA networks with an emphasis on the ability of the NCC to deliver centralised FMT management to a multitude of RCSTs simultaneously affected by rainfield attenuation. A possible FMT compatible with DVB-RCS has been described and the methods and supported by the standard mechanisms through which the proposed FMT can be implemented have been investigated. It is believed that the space-time model of rain attenuation is appropriate for the analysis of resource allocation for MF-TDMA networks in the presence of rain fading. The proposed methodology will consider the impact of rain attenuation magnitude, actual traffic characteristics of the user stations, spatial characteristics of rain as well as users' location and density on the overall achievable user capacity.

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