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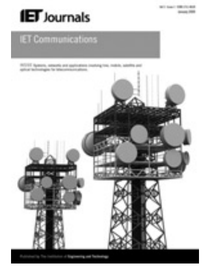

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Accurate modelling of Ka-band videoconferencing systems based on the quality of experience

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Abstract: Ka-band satellite multimedia communication networks play important roles because of their capability to provide the required bandwidth in remote places of the globe. However, because of design complexity, in practice they suffer from poor design and performance degradation because of being practically forced to guarantee acceptable end-user satisfaction in conditions of extremely low bit error rates, which is emphasised with the vulnerability of compressed video content to transmission errors, often impossible to be applied during the service development phase. A novel discrete event simulation model is presented, which provides performance estimation for such systems based on subjective measurement and a better quality of experience. The authors show that the proposed model reduces implementation cost and is flexible to be used for different network topologies around the globe.

1 Introduction

The broadband access market is dominated by digital subscriber line and cable modem technologies. However, these technologies are not readily available in remote rural areas, where Internet access still relies on slow dialup links. The TWISTER project, which was funded by the European Commission, has explored the feasibility of adopting Ka-band satellite technologies to deliver broadband services in rural areas through the installation of the technology at a number of validation sites, one of which was used to deliver e-learning content between the University of Malta and its branch on the neighbouring island of Gozo. The latter channel enabled the characterisation of the communications link and, hence, the development of an accurate simulation tool capable of predicting the end quality of video systems as perceived by the user.

The effect of the propagation phenomena present between earth–satellite links increases significantly with increasing frequency, where attenuations of around 20 dB may occur [1]. This makes it difficult to provide Ka-band satellite services at availability levels and quality comparable with similar systems operating at lower frequencies. Powerful forward error correction (FEC) schemes are generally adopted in wireless communication systems to minimise the errors introduced by the channel. However, minimising the bit error rate (BER) does not always result in increasing the end-to-end quality of a communication system, especially when dealing with multimedia codecs, which employ variable length codes (VLC) to achieve high compression ratios [2]. This makes the system more vulnerable to transmission errors, where a single corrupted bit may result in a burst of corrupted pixels which propagate in both spatial and temporal domains providing a significant degradation in visual quality [3].

The design of multimedia systems, to transmit over a Ka-band satellite channel, is not straightforward. The performance of the communication link is affected by the geographical location of the earth stations, link characteristics and the FEC schemes being adopted. The large number of parameters, concerned with the quality of a multimedia system, makes the design of such a system extremely complicated and, hence, the need for a simulation tool that facilitates the design of such systems arises.

Some analysis and modelling techniques of video traffic are available in the literature [4, 5], and in [6], the authors have done some work in predicting the end-to-end quality of audio over digital video broadcasting - return channel via satellite (DVB-RCS) channels. Transmission of video content over a terrestrial code division multiple access (CDMA) system was considered in [7–9], where the performance of the system was evaluated using direct computer simulation. However, this solution is highly computational intensive, especially when dealing with complex FEC schemes such as Reed–Solomon and turbo codes. To minimise the computational burden, importance sampling (IS) was adopted in [10]. However, although IS achieves a significant gain in performance over direct simulation, the resources required to simulate complex FEC schemes are still huge. An experimental study was presented in [11], where the authors have studied the end-to-end quality of a videoconferencing system using measured fading patterns. These fading patterns cannot be exported directly to other sites since fading statistics are dependent on the meteorological information, link characteristics and actual location of the earth station. This work is therefore not flexible and cannot be used to model systems situated at different locations around the globe.

This paper presents a fast, flexible and accurate discrete event simulation (DES) model of a typical multimedia communication system. Through this model, a number of design parameters and link characteristics can be varied in order to optimise the multimedia system in terms of the quality of experience (QoE) rather than the BER. Hence, this model lends itself to the network planning stage where its application helps in the design of reliable video systems based on human perception.

The rest of the paper is organised as follows. The videoconferencing system considered in this work is provided in Section 2. The proposed DES model is presented in Section 3, followed by the delivery of simulation results in Section 4. Finally, comments and conclusion are presented in Section 5.

2 Videoconferencing system

The video system considered in this work, and illustrated in Fig. 1, is used to deliver e-learning content between the University of Malta and its branch in Gozo. This system utilises TANDBERG camera equipment together with EUTELSAT's SKYPLEX module and Hot-Bird 6 satellite located at 13°E. The multimedia session is transmitted over a full-duplex channel at a data rate of 1056 kbps (528 kbps uplink and 528 kbps downlink).

Two TANDBERG cameras, which support the H.263++ video coding standard [12] are placed one at each end of the network to provide virtual real-time communication between the remote sites. The cameras transmit the compressed information encapsulated within real-time protocol, user datagram protocol and Internet protocol (IP) [13]. The IP datagrams are then transported to the SKYPLEX module over Ethernet. The multi-protocol encapsulation (MPE) allows the transmission of IP datagrams within MPEG-2 TS frames [14]. The maximum transfer unit of MPEG-2 TS is 184 Bs and, thus, MPE frames are usually segmented into a number of MPEG-2 TS frames. The MPEG-2 TS frames are protected using the DVB-RCS turbo codes [15] for the uplink channel and DVB-S concatenation codes [16] for the downlink.

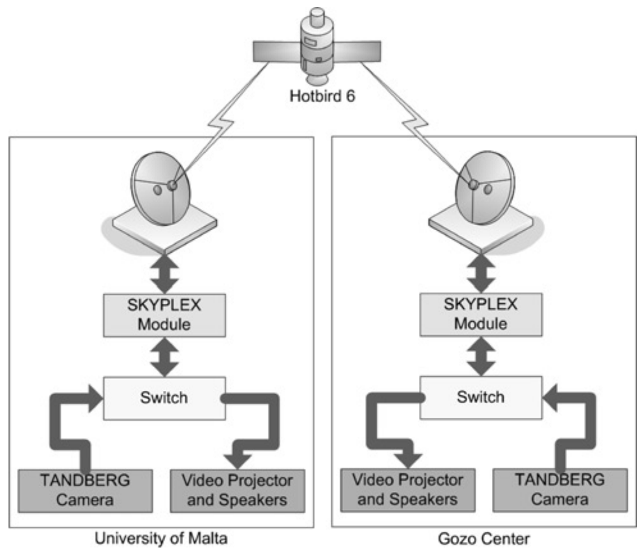

Figure 1 *Multimedia system considered in this work*

3 Videoconferencing DES model

The videoconferencing DES simulator is modelled using OPNET Modeler™ [17], which is the industry's leading environment for network modelling and simulation. The model specification of OPNET Modeler™ is organised in a three-level hierarchy structure, namely network, node and process models. The network models are made up of sub-networks and node models, the latter being objects in a network representing the equipment being used, whereas the process models control the module behaviour and represent a low-level description of the network model.

Fig. 2 illustrates a block diagram of the proposed DES model. It is divided into three sub-network models: the source network model, the satellite network model and the sink network model. The original video sequences are encoded by the H.263++ encoder that encapsulates the resulting compressed bitstream within the TANDBERG protocol stack shown in Fig. 3*a*. The resulting IP datagrams are transported to the SKYPLEX module over Ethernet where they are encapsulated within MPE frames, shown in Fig. 3*b*, and transported to the Hotbird 6 node using MPEG-2 TS frames.

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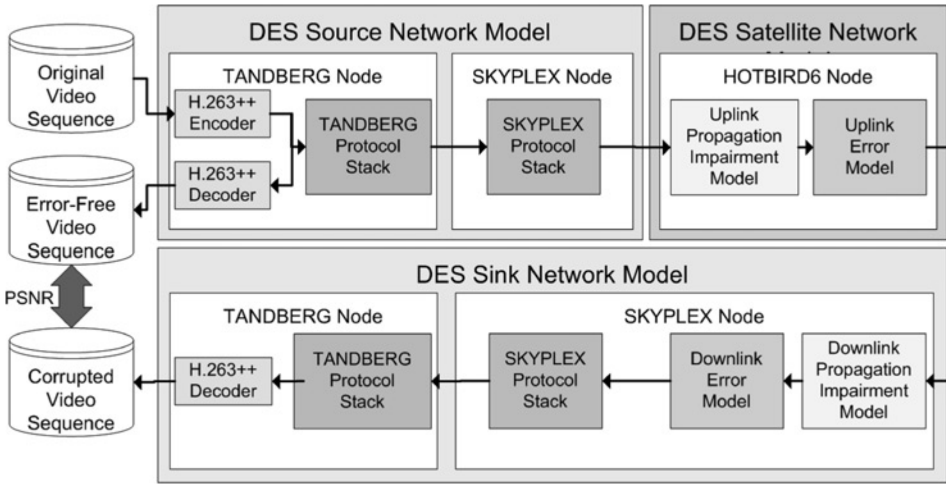

Figure 2 *Videoconferencing system DES model*

The propagation impairments present between the earth–satellite and satellite–earth links are modelled within the propagation impairment model. The error models are used to emulate the performance of the FEC schemes employed by the multimedia system for both the uplink and downlink channels. The corrupted MPEG-2 TS frames are received at the receiving node and the recovered IP datagrams are forwarded to the H.263++ decoder process that tries to recover the transmitted video sequence. The end-to-end quality is then evaluated using both the objective peak signal-to-noise ratio (PSNR) and the subjective double stimulus impairment scale [18].

3.1 Propagation impairment model

The propagation impairments affecting a Ka-band earth–satellite link include the attenuation because of gaseous absorption, clouds, precipitation, tropospheric scintillation and cross-polar interference [19]. These atmospheric phenomena can be accurately measured by means of satellite beacon signals and radiometers. However, since propagation experiments are carried out only in a few places around the world and for limited frequency bands, these results cannot be reliably applied to other sites. This is mainly because these propagation impairments are dependent on the link characteristics and the local weather of the earth station.

Long-term statistical models based on meteorological data and link characteristics are available in the literature. Different propagation impairment models were considered during this study, and those models, which best represent the individual propagation phenomena, are integrated within the DES model. Table 1 summarises the propagation impairment models adopted by the proposed model, whereas Fig. 4 illustrates the performance of both the uplink and downlink channels. More details and results are available in [20].

3.2 Error model

Wireless communication systems generally utilise powerful FEC schemes to minimise the BER. However, this does not necessarily result in improving the end-to-end quality of a videoconferencing system. The severity of the bit errors affecting the video quality depends on the spatial and the temporal location of the error [2].

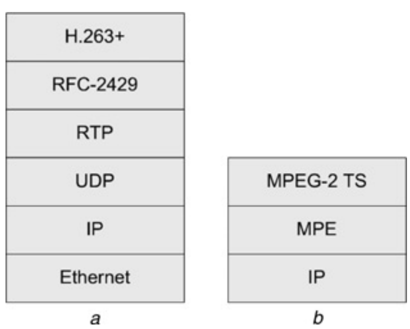

Figure 3 *Protocol stack employed by the videoconferencing system*

a TANDBERG protocol stack
b SKYPLEX protocol stack

Table 1 Propagation impairments models adopted by the DES model

Propagation impairment	Propagation impairment model
gaseous absorption	ITU-R P.676-5 [19]
cloud attenuation	ITU-R P.840-3 [20]
rain attenuation	ITU-R P.618-7 [21]
tropospheric scintillation	Van De Kamp [20]
cross-polar interference	ITU-R P.618-7 [21]
combined attenuation	castanet-Lemorton [23]

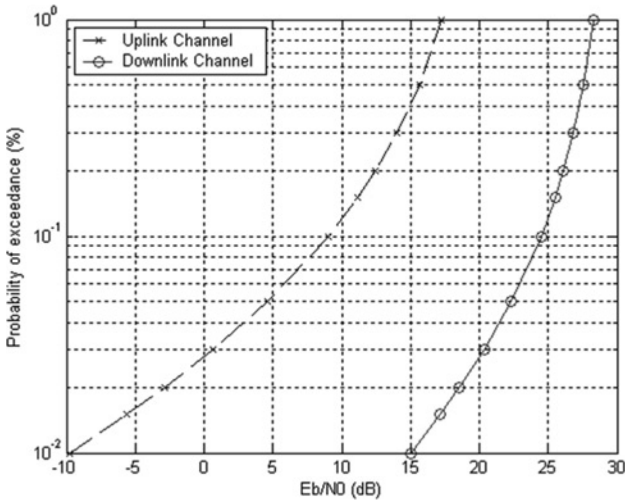

Figure 4 *Performance of both the uplink and downlink channels*

A Monte Carlo (MC) simulator [21] can be used as a reference error model, since it can accurately derive the spatial and temporal locations of the errors present in a channel. However, MC simulators require a huge amount of resources when simulating complex coding architectures and therefore cannot be employed directly within the DES model.

The error model employed in the proposed DES simulator emulates the performance of the FEC schemes employed by the system. This error model is based on the fact that for any packet switched network transmitting over an error prone channel, a packet may be either corrupted or uncorrupted, and each corrupted packet contains a number of corrupted bits. This scenario, as illustrated in Fig. 5, can be modelled by a three-random variable model, which is defined as follows:

- The frame error separation (FES) that represents the number of uncorrupted frames between two consecutive corrupted frames.
- The number of errors per corrupted frame (NECF) that represents the total number of corrupted bits present in each corrupted frame.

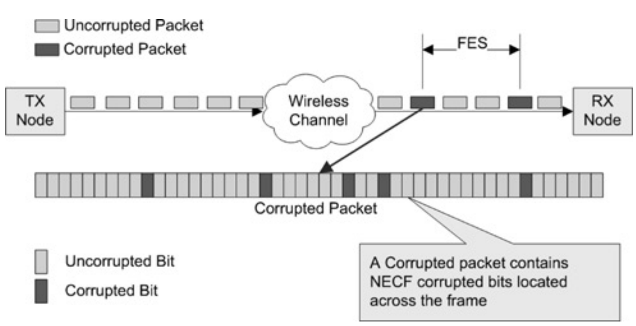

Figure 5 *Schematic diagram of the three-random variable model*

- The error location (EL) that represents the location of each corrupted bit within each corrupted frame.

Both DVB-RCS turbo codes and DVB-S concatenated codes were simulated using MC techniques with a confidence interval of 95% and a tolerance of 10%. The means μ_{FES} and μ_{NECF} and variances σ^2_{FES} and σ^2_{NECF} were derived from the FES and NECF data sets, respectively. These parameters were used to derive the probability density function, which approximates the FES and NECF distributions. Both the data sets were binned and the chi-square test was used to measure the difference between the binned distribution of the data set and the different standard distributions. In [22], the authors have concluded that for both the DVB error control schemes, the FES can be approximated by an exponential distribution, whereas the NECF can be approximated by a Gaussian distribution.

To comply with ITU radio regulations and to ensure adequate binary transmissions, serial data bitstreams are randomised [23]. Both the DVB error control schemes randomise the location of the errors, and therefore the EL distribution can be assumed to be uniformly distributed along the frame. The performance of the proposed error model and the reference MC simulations in terms of BER were presented in [22], whereas its performance in terms of PSNR is summarised in Tables 2 and 3. From these results, it is evident that the discrepancy between the two models is negligible.

The behaviour of the two FEC schemes adopted by the videoconferencing system is, thus, emulated without considering the details of the mechanisms involved in generating the error patterns that would otherwise be necessary in direct simulation. The emulation of these error models provides a significant gain in computational speed with minimal loss in accuracy when compared with the direct simulation method and is therefore adopted by the DES model.

Table 2 DVB-RCS video quality evaluation

Sequence	EB/No	PSNR-Y (proposed model)	PSNR-Y (reference model)
foreman	3.0	16.8430	17.0998
bus	3.0	15.7447	15.4968
foreman	3.5	20.1439	19.5192
bus	3.5	19.8745	20.1344
foreman	4.0	37.7835	38.1240
bus	4.0	35.0258	34.7710

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Table 3 DVB-S video quality evaluation

Sequence	EB/No	PSNR-Y (proposed model)	PSNR-Y (reference model)
foreman	3.0	17.5107	18.3258
bus	3.0	14.7013	15.0342
foreman	3.5	25.0420	27.2648
bus	3.5	19.8575	20.3346
foreman	4.0	42.5490	42.6925
bus	4.0	33.8300	33.7165

3.3 H.263++ codec

The videoconferencing system employs the H.263++ video coding standard to deliver real-time multimedia content between two remote sites. This codec supports two coding modes: (1) INTRA mode, where a video frame is considered as an independent still image and therefore only spatial redundancy is removed, and (2) INTER coding mode that encodes the difference between the previous and current frames and therefore removes both spatial and temporal redundancy. To achieve high compression ratios, VLC codes are adopted. However, the resulting system is more vulnerable to transmission errors where a single corrupted bit will result in a burst of corrupted macroblocks, from which artefacts will propagate in both the spatial and the temporal domains. This will significantly reduce the perceptual quality of the reconstructed video sequence.

4 Simulation results

The DES simulation environment is used to test different simulation scenarios. The first scenario consists of predicting the satellite link performance at different levels of availability. The traffic of a 1 h videoconferencing session at a data rate of 512 kbps is simulated. From these results, it is concluded that the downlink channel operates under an error-free condition since it has a large SNR even under heavy precipitation. Therefore the DVB-S error control scheme is robust enough to provide a quasi-error-free connection for the downlink channel. This is not the case for the uplink channel that is transmits at a higher frequency. The performance of the uplink channel is dependent on a set of parameters whose value should be optimised during the design stages. As an example, Fig. 6 illustrates the effect of the transmission power and that of the data rates on the performance of the system. This tool can be used to select an optimal set of parameters, which provide an acceptable end-user experience.

To completely evaluate the end-to-end perceptual quality of the videoconferencing system, six different video sequences were transmitted through the DES simulation environment; Erik, Akiyo, Silent, News, Football and Tennis. The resulting compressed video bitstreams, whose patterns are derived using the error model described above, are corrupted at different error rates and the resulting quality of the reconstructed videos is objectively and subjectively evaluated. The subjective categorisation of the video sequences was scaled using a methodology similar to the single stimulus test [24] and adopted in [25]. The 18 viewers used in the subjective test had to scale the quality of the video sequences between one and five, where one stands for very annoying and five stands for a good quality video. The mean opinion score is then used to provide a subjective rating of the distortion level. The objective and subjective results are summarised in Tables 4 and 5, respectively. The difference in the PSNR between the video sequences is mainly attributed to the broad range of movements considered in these test video sequences. However, in general, large values of the PSNR stand for high-quality videos and vice versa.

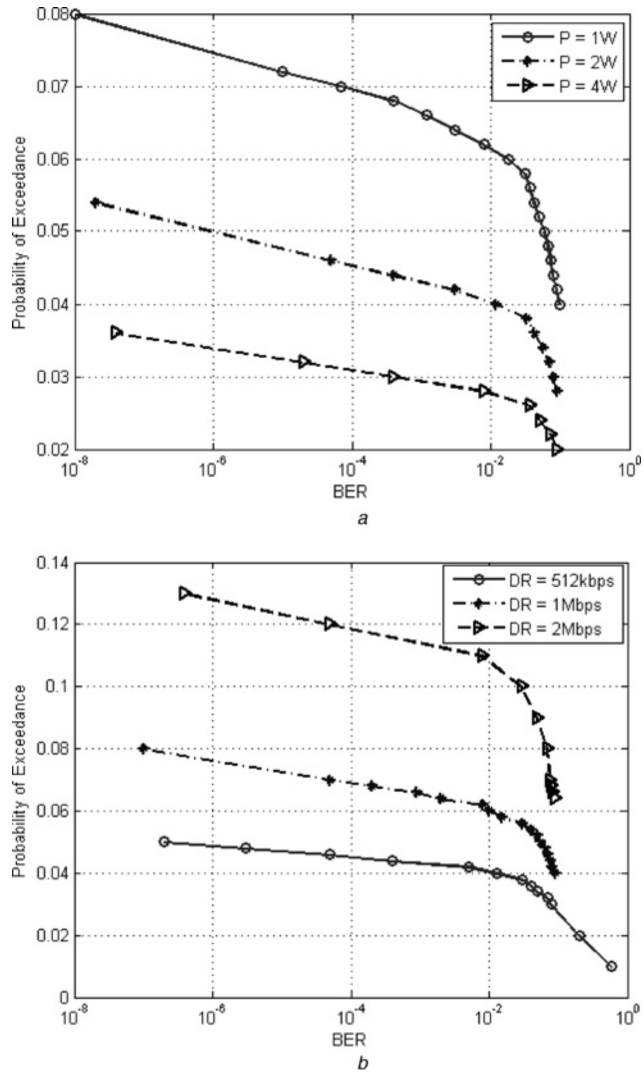

Figure 6 *BER performance curve of the uplink channel for:*

a Different transmission power levels
b Different data rates

Table 4 Objective evaluation of the quality of the system in dB

BER	Erik	Akiyo	Silent	News	Football	Tennis
3.59×10^{-1} (0.010%)	17.57	19.49	17.48	16.75	15.67	14.37
1.74×10^{-1} (0.020%)	17.13	16.46	17.35	16.91	16.05	14.01
8.03×10^{-2} (0.030%)	16.03	15.93	15.74	14.72	14.67	13.99
1.43×10^{-2} (0.040%)	15.72	17.34	15.09	14.34	15.86	13.88
2.37×10^{-3} (0.042%)	17.72	21.97	19.15	17.75	17.32	15.26
2.21×10^{-4} (0.044%)	23.16	27.87	26.03	23.31	21.38	18.52
1.27×10^{-5} (0.046%)	29.92	35.48	35.04	30.53	31.66	27.09
8.20×10^{-7} (0.048%)	33.55	38.56	35.30	32.06	34.10	27.37
4.10×10^{-8} (0.050%)	NA	NA	NA	NA	NA	NA

Table 5 Subjective evaluation of the quality of the system

BER	Erik	Akiyo	Silent	News	Football	Tennis
3.59×10^{-1} (0.010%)	1	1	1	1	1	1
1.74×10^{-1} (0.020%)	1	1	1	1	1	1
8.03×10^{-2} (0.030%)	1	1	1	1	1	1
1.43×10^{-2} (0.040%)	1	1	1	1	1	1
2.37×10^{-3} (0.042%)	1	1	1	1	1	1
2.21×10^{-4} (0.044%)	1	1	1	1	2	2
1.27×10^{-5} (0.046%)	2	2	2	3	3	3
8.20×10^{-7} (0.048%)	4	4	4	4	4	5
4.10×10^{-8} (0.050%)	5	5	5	5	5	5

Imperceptible = 5; perceptible but not annoying = 4; slightly annoying = 3; annoying = 2; very annoying = 1

A satisfactory end-user experience is provided at a BER less than 8.20×10^{-7}, which corresponds to 99.952% of the time when operating at a transmission power of 2 W and a data rate of 512 kbps. From the results, it is evident that at a BER greater than 2.37×10^{-3}, which corresponds to 0.042% of the time, almost all macroblocks are corrupted. In between these two cases of the BER, the quality of the system is poor but it can be enhanced if the errors are adequately detected. The performance of the standard H.263++ decoder is not effective in this because, on average, 40.54% of the corrupted macroblocks are not detected, resulting in a significant reduction in the quality of the system. The error resilient mechanisms offered by the standard decoder are therefore not robust enough to guarantee an acceptable QoE when transmitting over wireless channels. This problem can be alleviated by applying more advanced error-detection and concealment algorithms already present in the literature [26–28].

5 Conclusion

In this paper, we present a fast and accurate DES model to predict the perceptual quality as well as the availability of Ka-band videoconferencing systems.

The simulation results show that the proposed model can be configured to model the systems anywhere faster than the conventional simulation techniques. This model can be used in the design stages of DVB and videoconferencing multimedia systems. Hence, these systems can be designed with the aim of guaranteeing a certain level of the PSNR instead of the BER.

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The evaluation model is available at the University of Malta where a good video quality (subjective quality levels 4 and 5) is experienced for 99.952% of the time with the PSNR being always greater than 32 dB.

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