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ADVANCED COOPERATIVE AND COGNITIVE RADIO TECHNIQUES FOR RESOURCE MANAGEMENT IN MOBILE SATELLITE COMMUNICATIONS

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For my grandmother

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Contents

Part II Cooperative Communications in Satellite Systems

Part III Adoption of Cognitive Radio Strategies in Hybrid Satellite-Terrestrial Networks

List of Figures

List of Tables

Acronyms

3G	Third Generation
3GPP2	Third Generation Partnership Project 2
AAL 5	ATM Adaptation Layer 5
ACM	Adaptive Coding and Modulation
ADT	Application Data Table
AF	Amplify and Forward
APSK	Amplitude and Phase Shift Keying
ARTEMIS	Advanced Relay and Technology Mission Satellite
ATM	Asynchronous Transfer Mode
AWGN	Additive White Gaussian Noise
BB	BaseBand
BC	Backwards-Compatible
BCH	Bose Chaudhuri and Hocquenghem
BEC	Binary Erasure Channel
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BSM	Broadband Satellite Multimedia
CC	Convolutional Codes
CCM	Constant Coding and Modulation
CDF	Cumulative Distribution Function
CER	Codeword Error Rate
CGC	Complementary Ground Component
CM	Cognitive Manager
CR	Cognitive Radio
CRC	Cyclic Redundancy Check
CRSC	Circular Recursive Systematic Convolutional
CSC	Common Signalling Channel
DAMA	Demand Assigned Multiple Access

DF	Decode and Forward
DOCSIS	Data Over Cable Service Interface Specification
DOCSIS-S	Data Over Cable Service Interface Specification - Satellite
DS	Direct Sequence
DSL	Digital Subscriber Line
DSNG	Digital Satellite News Gathering
DVB	Digital Video Broadcasting
DVB-H	Digital Video Broadcasting - Handheld
DVB-RCS	Digital Video Broadcasting - Return Channel Satellite
DVB-RCS+M	Digital Video Broadcasting-Return Channel Satellite+Mobility
DVB-RCS NG	DVB-RCS Next Generation
DVB-S	Digital Video Broadcasting - Satellite
DVB-S2	Digital Video Broadcasting - Satellite second generation
DVB-SH	Digital Video Broadcasting - Satellite services to Handhelds
DySPAN	Dynamic Spectrum Access Networks
ESA	European Space Agency
ETSI	European Telecommunications Standards Institute
EV-DO	Evolution Data Only
FCC	Federal Communications Commission
FEC	Forward Error Correction
FSS	Fixed Satellite Service
FTP	File Transfer Protocol
GMES	Global Monitoring for Environment and Security
GPS	Global Positioning System
GSE	Generic Stream Encapsulation
GSM	Global System for Mobile Communications
GW	Gateway
HDTV	High Definition Digital Television
HLS	Higher Layer Satellite
HP	High Priority
HPA	High Power Amplifier
HSPA	High Speed Packet Access
IEEE	Institute of Electrical and Electronics Engineers
IPL	Inner Physical Layer
IP	Internet Protocol
IPoS	IP over Satellite
ITU	International Telecommunication Union
LDPC	Low Density Parity Check
LEO	Low-Earth-Orbiting
LL-FEC	Link Layer-Forward Error Correction
LLR	Log-Likelihood Ratio

LMS	Land Mobile Satellite
LOS	Line-of-sight
LP	Low Priority
MAC	Medium Access Control
MF-TDMA	Multi Frequency - Time Division Multiple Access
MIMO	Multiple Input Multiple Output
MPE	Multi Protocol Encapsulation
MPE-FEC	MPE Forward Error Correction
MPE-IFEC	MPE Inter-burst Forward Error Correction
MPEG	Moving Pictures Experts Group
MSB	Most Significant Bit
N_{atm}	Number of ATM cells in an ATM Traffic burst (1, 2 or 4)
NCC	Network Control Centre
NGN	Next Generation Network
NLOS	Non-line-of-sight
ODU	Outdoor Unit
OFDM	Orthogonal Frequency-Division Multiplexing
OPL	Outer Physical Layer
O-PSK	Offset-Phase Shift Keying
PDF	Probability Density Function
PDU	Protocol Data Units
PER	Packet Error Rate
PID	Packet Identifier
PL	Physical Layer
PLR	Packet Loss Ratio
PSK	Phase Shift Keying
PSTN	Public Switched Telephone Network
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RCST	Return Channel Satellite Terminal
RF	Radio Frequency
RS	Reed-Solomon
SC	Satellite Component
SCC	Standards Coordinating Committee
SDR	Software-Defined Radio
SF	Selective Forwarding
SFN	Single Frequency Network
SINR	Signal-to-Noise-Interference Ratio
SI-SAP	Satellite-Independent Service Access Point
SM	Satellite Modem

SMTS	Satellite Modem Termination System
ST	Satellite Terminal
TBTP	Terminal Burst Time Plan
TCP	Transmission Control Protocol
TDM	Time Division Multiplex
TDMA	Time Division Multiple Access
TG	Traffic Gateway
TIA	Telecommunications Industry Association
TPS	Transmission Parameters Signalling
TS	Transport Stream
UMTS	Universal Mobile Telecommunications System
VCM	Variable Coding and Modulation
VoIP	Voice over IP
VPN	Virtual Private Network
VSAT	Very Small Aperture Terminal
WG	Working Group
WRAN	Wireless Regional Area Network

Introduction

Satellites have assumed a key role in the telecommunications field, due to their peculiar capabilities. In fact, they allow the extension of the coverage area of terrestrial, fixed and mobile, networks and, moreover, they are not damaged by disasters occurring on the Earth surface, so they can assume a crucial role in operations carried out to save human lives in case of emergency situations.

Furthermore, satellite communications have developed a global success in the field of digital audio/TV broadcasting, just because they offer a wide coverage area and, therefore, they are very suitable for the distribution of multimedia contents to a large number of potential users, also in rural environments.

Considering the increasing exploitation of satellite resources and the large available bandwidth, for example in *Ku* and *Ka* bands, it appeared a natural consequence to extend satellite services to realise fully interactive broadband communications with, at least, the same access capabilities offered by terrestrial wired networks (xDSL).

Furthermore, in addition to the provision of satellite multimedia services to fixed terminals, people are getting more and more eager to be able to establish broadband communications on the move (ships, trains, aircrafts, vans, cars). This can be gather from the huge number of mobile telephones subscriptions which have exceeded fixed line subscription in many countries. Higher data rates for mobile devices are already provided by new standards such as UMTS, HSPA and EV-DO, [1]-[2].

In this general context, various standardisation institutions have developed satellite standards in order to fill up the gap between satellite and terrestrial communications. In particular, in Europe, due to the successful introduction of DVB-S standard, [3], developed by the DVB (Digital Video Broadcasting) Project, [4], a promising technical foundation has been laid for the development of satellite communications. The second generation of DVB-S, named DVB-S2, [5]-[6], as well as DVB-RCS, [7]-[8], standards are, currently, generally accepted, respectively, as the forward (gateway-to-user) and the return (user-to-gateway) links for satellite systems which support multimedia services. New standards for mobile broadcasting are also appeared and they are consolidating, as, for example, the DVB-SH, [9]-[10]-[11].

At present, broadband access and dedicated point-to-point links (e.g. for professional services) are primarily supplied by terrestrial networks and broadband satellite communication services are still a niche market, especially for mobile users. However, many transport operators are involved in the provision of TV services in ships, trains, vans and aircrafts, and Internet access to passengers through GSM and UMTS mobile platforms by using satellite connectivity for backhauling. Moreover, following this plan of action, also DVB-RCS standard has been adapted for the usage in mobile environments [12], in order to be able to combine digital TV broadcast reception in mobile environments (AirTV, luxury yachts, trains, etc.) and IP multimedia services.

Considering such a increasing demand of satellite communications, the research activity developed during the Ph.D. Program has been focused on this area, in particular on the study of different transmission and reception techniques which allow improving the performance of satellite users displaced in severe environments and increasing the efficiency in the usage of radio spectrum resources in case satellite and terrestrial systems “coexist”, for different reasons, in a certain area. Such an investigation has considered different application scenarios, only satellite and hybrid satellite and terrestrial, with particular attention to mobile environments. The analysis of this context has detected the need to adequate advanced techniques to achieve a sufficient quality in satellite links, especially in the uplink where the link budget is usually tighter.

These considerations have motivated the study of *cooperative techniques* which allow mitigating the deleterious effects of fading thanks to a new form of spatial diversity in which the diversity gain can be achieved through the cooperation of different users which generate a virtual MIMO system, and the adoption of strategies based on the concept of the *Cognitive Radio* which defines an intelligent system which allows a flexible and efficient use of radio spectrum by providing terminals the ability of *sensing* and *dynamic spectrum sharing*.

More specifically, two *cooperative* approaches, called *Coded-Cooperation* and *Selective Forwarding Cooperation* have been investigated. *Coded-cooperation* relies on the idea that the bits of each produced codeword are transmitted in the satellite uplink by different cooperative terminals, thus permitting to achieve virtual long interleaving while *Selective Forwarding Cooperation* is based on the concept that users devoted to cooperation, called “cooperators”, repeat packets of the users which require to transmit their informative data, called “active users”, through different independent channel paths with the condition that only the successfully decoded packets received from active users, are sent toward the final destination. Under some assumptions, this methodology can permit to achieve a diversity order equal to the number of users involved in a transmission.

Concerning, instead, the *Cognitive Radio* approach, a resource allocation strategy for *spectrum sharing*, based on a heuristic algorithm, has been developed. In this case, a *Cognitive Radio* system without license, called *secondary* system, can coexist with a

primary system, which is license owner, and it is able to transmit its own information data without producing harmful interference to the *primary* system.
This work reports the analysis performed and the main results achieved in the carried out research activity. It is divided in three main Parts:

- *Satellite Communications*
- *Cooperative Communications in Satellite Systems*
- *Adoption of Cognitive Radio Strategies in Hybrid Satellite-Terrestrial Networks*

In the first Part, *Chapter 1* presents a general overview on the new trends in satellite communications, starting from a state-of-the-art of satellite technologies and highlighting the new key role assumed nowadays by satellite communications. *Chapter 2* and *Chapter 3*, instead, deal with the key features of main broadcasting satellite systems and the current major trends worldwide in satellite communications concerning interactive and broadband applications, respectively.
The second Part reports the investigation on the adoption of *cooperative communications* in critical mobile satellite scenarios. Starting from a general overview on *cooperative communications* and, in particular, on the selected cooperative approaches reported in *Chapter 4*, in *Chapter 5*, the performance achieved by satellite interactive terminals which exploit *Coded-Cooperation* in a land-vehicular scenario is reported. *Chapter 6* presents the simulated and theoretical outcomes resulting from the adoption of *Selective Forwarding* cooperation techniques at Physical layer while *Chapter 7* deals with the assessment of cooperation effects at MAC layer in satellite interactive systems. In particular, a modified resource allocation mechanism which implements a *Selective Forwarding* cooperation scheme within a group of sources is considered.
The third Part introduces, in *Chapter 8*, the *Cognitive Radio* concept, providing an overview on this novel approach while, in *Chapter 9*, shows the potential benefits coming from the adoption of a *Cognitive Radio* strategy for *spectrum sharing* in a context of coexistence of two systems.
At the end, some conclusions, including some directions for future developments, are provided.

Part I
Satellite Communications

Chapter 1
New Trends in Satellite Communications

Abstract This chapter presents a general overview on the new trends in satellite communications. The current and future growth of satellite communications crucially depends on the quality of technological innovation and the speed of its translation into operational services in order to increase market opportunities. Starting from a state-of-the-art of satellite technologies, the new key role assumed by satellite communications is described, taking into account different application scenarios.

1.1 A General Overview

Satellite communications have become an important node of the global telecommunication infrastructure. Nowadays, hundreds of millions of people watch television channels distributed via one of the approximately 250 commercial telecommunication satellites which are, currently, operational in geostationary orbit.

As highlighted in an ESA study, [13], satellite capacity request is growing quickly, driven not only by broadcast applications but, mainly, by broadband services, in particular by the expectation of "always-on" broadband services available everywhere. Thus, new "killer" applications as High Definition Digital Television (HDTV) and broadband Internet access, provided through satellites, can help to trigger higher growth rates of capacity request in the near future.

Furthermore, satellites of today are much more complex systems than those developed in the past. In most cases, they are no longer just mere repeaters that reflect incoming signals back to receivers. Today, on board of satellites, digital signal carrying all kinds of information can be processed, transformed and routed to their destinations according to the network conditions. Moreover, IP routers, (e.g. the *Cisco Space Router* [14]), are beginning to be deployed on board of satellites so that satellites are becoming part of Internet. They can make the network more accessible, more resilient and more versatile. One of the most interesting example about this new role of satellites,

Fig. 1.1 Telecommunications satellites (*Photo:, http://www.esa.int/images/telecom_hr_no_woman_1000x1000,0.jpg*)

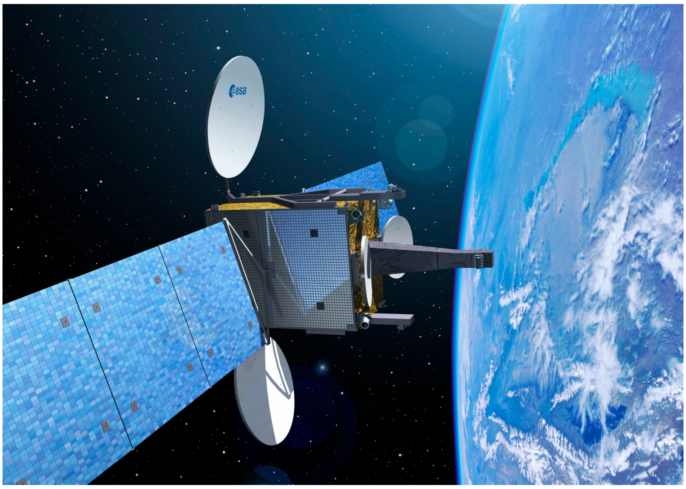

Fig. 1.2 ESA's Small GEO satellite (*Photo: ESA-P.Carril, http://www.esa.int/images/09801A4SmallGeoSatESACarril,0.jpg*)

is provided by Inmarsat, [15], which has developed a broadband global area network service for mobile terminals on land, at sea and in the air. Users can send and receive voice and data services nearly everywhere on Earth.

Such a successful result achieved by satellite communications, can be explained by considering the unique capabilities offered by satellite systems, first of all the very large coverage area available. Moreover, in some particular cases as the transoceanic maritime and aeronautical communications, satellites are the only practical solution to telecommunications requirements.

Broadband satellite systems can also help to bridge the digital divide because they can provide a rapid deployment compared with other terrestrial infrastructures, without gigantic investments. Continents (e.g. Africa) and large countries which, currently, lack in infrastructures could satisfy their needs (mobile phones, Internet access, etc.) and create new opportunities for human development. Applications like telemedicine, e-learning or simply an easy access to information can allow economic activities to grow and develop.

Then, another key feature is that, once in orbit, satellite systems are highly reliable and less vulnerable to disasters compared with the terrestrial infrastructures. In recent years, it has happened for several reasons (emergency situations, damages, etc.) that large areas would have been left without Internet access for several weeks, with potentially serious consequences for their economy, if there had not been satellite solutions to fall back on.

Furthermore, satellite-based systems cannot considered anymore just a complement component to terrestrial infrastructures. They can offer a complete competitive solution and become a real alternative to terrestrial systems. The next generation of satellite services considers radio and TV broadcast services and interactive broadband Internet access to mobile terminals. Such services can be also extended by ground components which can assist mobile users transmissions without the need to directional antennas.

Considering what has been done in the last years, it is worth highlighting the rapid multiplying, in Europe and in United States, of interactive solutions allowing a return path to be made via satellite links. The advent of new standards developed with strong effort by the DVB Project, [4], such as the DVB-S2 for the forward link and the DVB-RCS for the return link, has stimulated the commercialisation of such solutions.

First, new two-way satellite technologies were developed using standard-based technology only for the downlink and proprietary one for the return link. However, lately, satellite communications have moved towards open standards, also for the return link. In fact, in the satellite communication market, some industry standards have emerged and, although in the satellite broadband sector there are still several proprietary technologies in use, the emergence of some open standards can be noted.

Currently, there are three major trends worldwide in satellite communications concerning interactive and broadband applications: the open DVB-RCS standard, the proprietary *Internet Protocol over Satellite* (IPoS) standard and the *SurfBeam* system.

Despite its non-dominant market position because of higher cost terminal price, DVB-RCS is still the most promising open standard. Many equipment manufacturers have developed or are in the process of developing DVB-RCS compliant equipment making it the most widely adopted standard in terms of manufacturer numbers. Several manufacturers have also performed interoperability tests between various terminals against

different HUBs, under the coordination of the SatLabs interoperability group, [16]. On the contrary, the other two systems are currently implemented in a single platform and deployed by a single manufacturer.
The main satellite communication systems for broadcasting and broadband applications are described in more detail and compared in Chapter 2 and in Chapter 3.

1.2 Application Scenarios

Satellite systems can allow a multitude of valuable services and applications for public authorities and for private users, to emerge. The possible application scenarios can be not only telecommunication ones but also integrated services which draw on different aspects of space sector, such as navigation, communication, remote sensing and monitoring technologies.

1.2.1 Telecommunications Applications

The use of satellite for telecommunication, besides for commercial services such as broadcasting, multimedia transmission, broadband services for fixed and mobile terminals, is considered also for other application scenarios such as public services, emergency services, data relay services, etc. In the following, the new main applications are briefly described.

1.2.1.1 Public Services

Satellite services are gaining operational relevance in *public services*. For example, broadcasting services via satellite are an important tool of public diplomacy. Moreover, the monitoring and the protection of critical infrastructures such as pipelines and oil platforms, depend on data transmission via satellite. And also coastal and maritime security has increased thanks to the use of new satellite technologies suitable for tracking the position and the state of goods transported by sea. Vessels are required to carry satellite terminals that transmit their identity and position and can help in emergency situations. Finally, environmental and fishing regulations can be much better enforced thanks to the larger monitoring and control area at sea.

1.2.1.2 Emergency Applications

The benefits of satellite communications are well visible also in *emergency applications* wherein the world-wide Civil Protection is involved in order to guarantee safety to population. In case of floods, earthquakes, volcanic eruptions and other major disasters, terrestrial communication networks could be damaged and not be able anymore to provide the services required by first responder teams, such as, for example, a robust voice communication system. Rescue teams terminals should be also compatible with other different kinds of terminals if the disaster involves more than one country and so multinational rescue operations are needed. In such a situation, satellites can flexibly connect different first responder team clusters over large distance across incompatible standards, as shown in Fig. 1.3. In fact, for large disasters, only satellites are actually able to cover the whole scene and provide broadband services. Satellite are also well suited for providing the required degree of resilience that allows governments the continued operations and provision of essential services even in most severe contingencies, and private industries the business continuity, [13]. The use of satellite with multiple spot beams supports efficient management of the satellite capacity. For fixed and transportable systems, data rates of hundreds of kbit/s are possible, serving a variety of services. On the other hand, mobile systems are able to transmit reduced

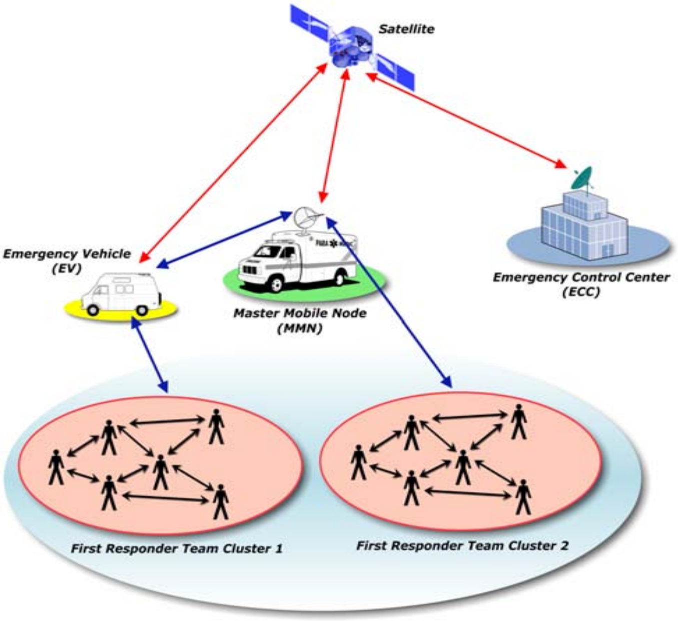

Fig. 1.3 Emergency scenario

data rate (several tens of kbit/s) but with the advantage of improved versatility in deployment. Finally, the regulation of the satellite related bands is already handled at an international level and this is certainly a strong point in favour of quick deployment and it also helps to devise a pan-European system.
However, there are also some drawbacks in using satellite in such scenarios, due to the physics of satellite transmissions and to the business models of the various satellite industry actors. First of all, satellite transmissions often require nearly LOS conditions and indoor operations must rely on gap filling. Moreover, the data rates achievable through a satellite system are tightly linked to the size and directivity of the antenna and the higher the data rate, the larger the antenna and the more accuracy is required for pointing. Finally, satellite capacity and equipment can be perceived as costly especially when there are terrestrial telecommunication technologies still active and available, [17]-[18].

1.2.1.3 Earth monitoring data transmission services

The increasing demand of monitoring global energy and food supplies, observing the world-wide climatic developments and keeping under surveillance the emissions in support of binding international commitments, requires a new high-capacity reliable data transmission infrastructure which can provide information at the right time. For example, concerning the environmental issues, GMES (Global Monitoring for Environment and Security) system, [19], will allow measurements such as wind, temperature, humidity, cloud coverage, waves, etc., in an encompassing, continuous and operational way. Therefore, it is fundamental to create a communication system able to transmit such a big flow of new data. In this context, satellite communications can be a crucial role both in its geostationary form and in lower earth orbits. Moreover, the data captured by sensor networks displaced on the Earth surface, can facilitate the detection and the early warning of natural disasters and, in this case, the role of satellites is still more crucial for spreading the alert quickly.

1.2.1.4 Data Relay services

The global monitoring will lead to an increasing demand of real-time data transmission, as already said above. In order to make the collected data available to scientists and authorities without delay, many of these will be routed through data relay satellites. The European Advanced Relay and Technology Mission Satellite (ARTEMIS), shown in Fig. 1.4, has been designed to test and operate such new telecommunications techniques. It carries, therefore, three payloads:

- a *L* band mobile payload;

- a laser-optical relay terminal;
- a double S/Ka band terminal.

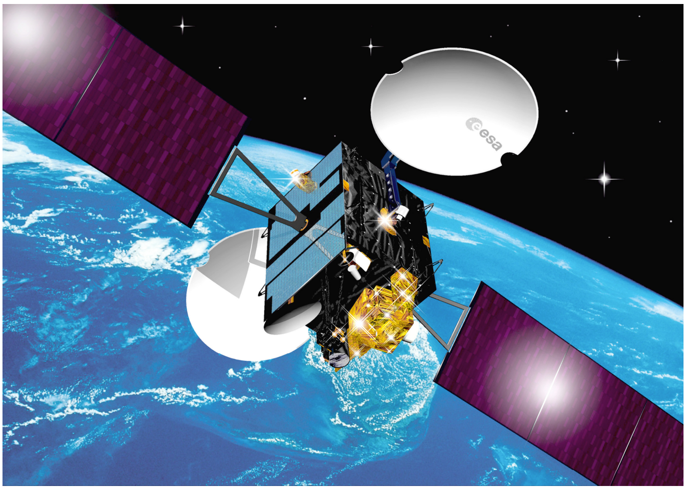

Fig. 1.4 Advanced Relay and Technology Mission Satellite (ARTEMIS) (*Photo: ESA-J.Huart, http://esamultimedia.esa.int/images/artemisAVhires.jpg*)

Fig. 1.5 ARTEMIS satellite and LEO satellite (SPOT 4) communicating via an optical link (SILEX system)(*Photo: ESA-J.Huart, http://esamultimedia.esa.int/images/navigation/corv_94.jpg*)

The first one allows two-way voice and data communications, via satellite, between fixed Earth stations and land mobiles - trucks, trains or cars - anywhere in Europe and North Africa whereas the other two payloads have been designed for communications directly between satellites and allow receiving data from Low-Earth-Orbiting (LEO) satellites (Fig. 1.5) and transmitting them directly to Europe.

1.2.1.5 Air Traffic Management

A satellite communication component is considered in the Air Traffic Management scenario (Fig. 1.6), as well. Also in this application, the main satellite communication strengths are the large coverage area and the rapid deployment. Thanks to the use of satellites, a seamless service between air traffic controllers and pilots could be provided in Europe, including not only areas of dense traffic but also remote areas such as Mediterranean sea, transatlantic routes, deserts, etc., [13].

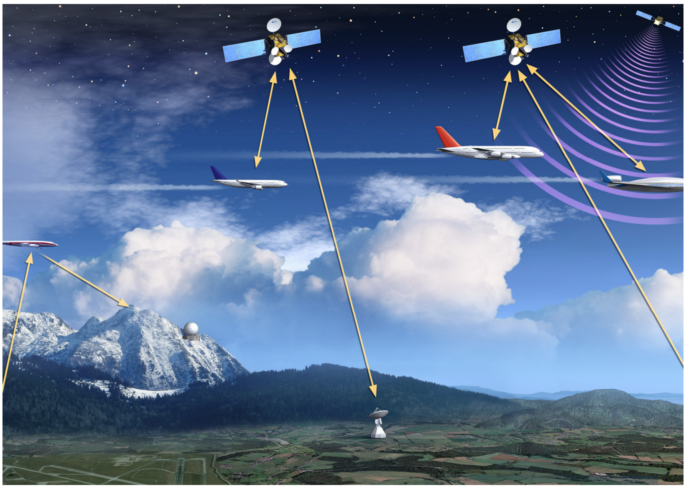

Fig. 1.6 Iris: ESA programme for satellite communications for air traffic management (*Photo: ESA-P.Carril, http://esamultimedia.esa.int/images/telecom/Iris-01C-2D-MR_H.jpg*)

1.2.2 Integrated Applications

Integrated applications use various aspects of satellite technology (Fig. 1.7). For example, positioning data from GPS and Galileo (Fig. 1.8) and transmission data via satellite can be combined for location-aware services, as well as remote sensing, navigation and communication can be linked for other particular purposes. Some exam-

Fig. 1.7 Integrated applications, satellites for communication, navigation, observation, monitoring, (*Photo: ESA, http://www.esa.int/images/INTEGRATED_APPL_1000x1000.jpg*)

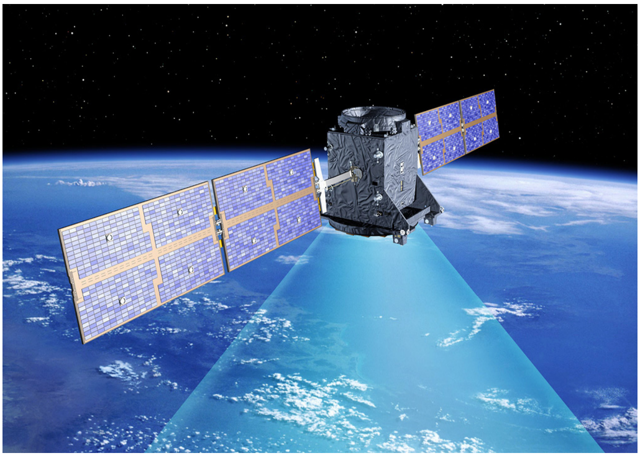

Fig. 1.8 Galileo navigation satellite system: GIOVE-A in orbit (*Photo: ESA-P.Carril, http://esamultimedia.esa.int/images/galileo/GSTB_satellite/GSTBV2A_LR_02B_H.jpg*)

ples of integrated application scenarios are the following:

- *Safety*: new integrated navigation and communication satellite services need to be developed and used for public safety. For example, through satellites, maritime surveillance can be extended beyond the coastal areas and new potential maritime attacks can be prevented (Fig. 1.9).
- *Emergency, Crisis Management and Peace building*: the combination of telecommunications, observation and positioning resources can be very useful in case of emergencies, in particular for the assistance in remote areas, for medical services in emergency conditions and for peace support operations.
- *Health*: the integration of Earth observation and geo-positioning systems which merge current data on disease cases with environmental, meteorological and socio-economic conditions can help doctors and public health authorities to prevent the spread of epidemic diseases.

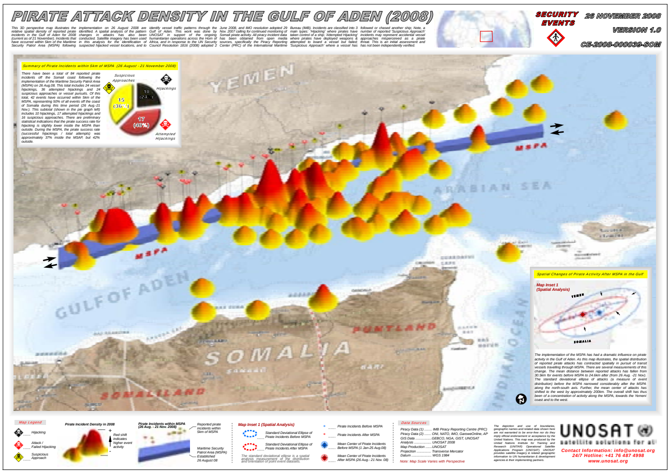

Fig. 1.9 Pirate Attack Density in the Gulf of Aden (2008) (*Photo: UNOSAT and IMB Piracy Reporting Centre, http://unosat.web.cern.ch/unosat/freeproducts/somalia/Piracy/UNOSAT_SO_PirateDensity_Nov08_Lowres_v1.pdf*)

Chapter 2
New Broadcasting Satellite Systems

Abstract In this chapter the key features of two main broadcasting satellite systems, developed by the DVB Project for fixed and mobile services, are introduced. In particular, the second generation of the well-known DVB-S system, called DVB-S2, has achieved a great success and it is, currently, generally accepted as the forward link for satellite systems which support multimedia services. On the other hand, the more recent DVB-SH is consolidating its role in the field of mobile satellite communications and it is very promising for the future commercial mobile-TV applications.

2.1 The DVB-S2 System

DVB-S2 is the second-generation specification for satellite broadcasting, developed by the DVB Project, [4], starting from 2003. It benefits from more recent developments in channel coding (LDPC codes) combined with a variety of modulation formats (QPSK, 8PSK, 16APSK and 32APSK). When used for interactive applications, such as Internet applications, it may implement an *Adaptive Coding and Modulation* (ACM) scheme, thus optimizing the transmission parameters for each individual user, dependant on path conditions. Backwards-compatible modes are available, allowing existing DVB-S set-top-boxes continuing working during any transitional period, [5], [6]. The DVB-S2 system has been designed for several satellite broadband applications, [20]:

- broadcast services for standard definition TV and HDTV, (*Broadcast* profile);
- interactive services, including Internet access, for consumer applications, (*Interactive* profile);
- digital TV contribution and Satellite News Gathering, TV distribution to terrestrial VHF/UHF transmitters, (*DSNG* profile);

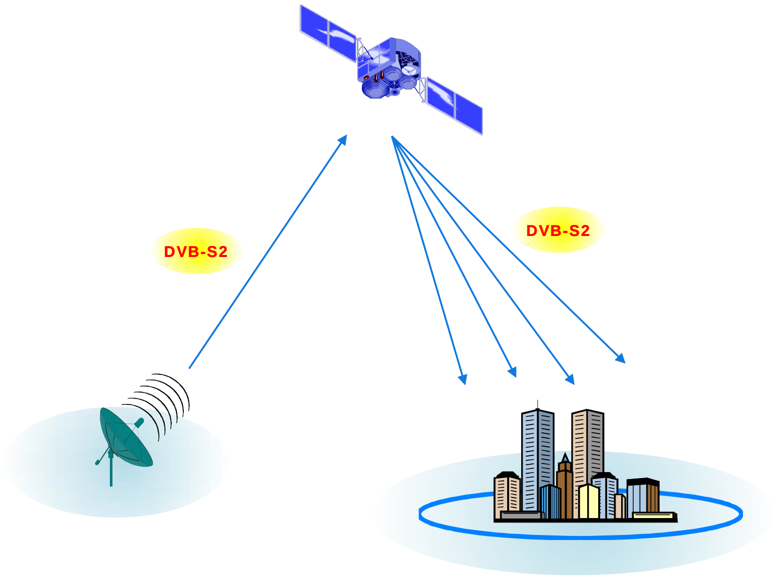

Fig. 2.1 DVB-S2 scenario

- data content distribution and trunking and other professional applications, (*Professional* profile).

It is based on a “tool-kit” approach which allows covering all the application areas while still keeping the single-chip decoder at reasonable complexity levels, thus enabling the use of mass market products also for professional applications.
The DVB-S2 standard has been specified around three key concepts:

1. best transmission performance
2. total flexibility
3. reasonable receiver complexity

To achieve the best performance complexity trade-off, quantifiable in about 30% capacity gain over DVB-S, [3], DVB-S2 makes use of more recent developments in channel coding and modulation. For interactive point-to-point applications such as IP unicasting, the adoption of the ACM functionality allows optimising the transmission parameters for each individual user on a frame-by-frame basis, dependant on path conditions, under closed-loop control via a return channel (terrestrial or by satellite): the result is an even greater gain of DVB-S2 over DVB-S.
DVB-S2 is so flexible that it can cope with any existing satellite transponder characteristics, with a large variety of spectrum efficiencies and associated C/N [1] requirements. Furthermore, it is not limited to MPEG-2 video and audio coding, but it is designed

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[1] Carrier-to-noise power ratio (N measured in a bandwidth equal to symbol rate)

to handle a variety of advanced audiovideo formats like the *Generic Stream* format, [21]-[22], which the DVB Project has recently defined (for more details see 2.1.4). DVB-S2, therefore, accommodates to any input stream format, including single or multiple MPEG Transport Streams, continuous bit-streams, IP as well as ATM packets.

2.1.1 Channel coding and Modulation

The DVB-S2 system is characterised by an efficient and powerful FEC enconding scheme which allows achieving excellent performance by satellite, in presence of high levels of noise and interference. The adopted channel coding scheme is composed by a concatenation of BCH outer codes and LDPC inner codes. The selected LDPC codes use very large block lengths: 64800 bits (*normal FEC frame*) for applications not too critical for delays, mainly used in the *Broadcast* profile, and 16200 bits (*short FEC frame*) mainly considered in the *Interactive* and in *Professional* profiles. Code rates of $1/4$, $1/3$, $2/5$, $1/2$, $3/5$, $2/3$, $3/4$, $4/5$, $5/6$, $8/9$ and $9/10$ are available, depending on the selected modulation and the system requirements. Coding rates $1/4$, $1/3$ and $2/5$ have been introduced to operate, in combination with QPSK, under exceptionally poor link conditions, where the signal level is below the noise level. Concatenated BCH outer codes are introduced to avoid error floors at low Bit Error Rates (BER).

Four modulations can be selected for the transmitted payload, as it can be seen in Fig. 2.2. QPSK and 8PSK are typically proposed for broadcast applications, since they are virtually constant envelope modulations and can be used in non-linear satellite transponders driven near saturation. The 16APSK and 32APSK modes, mainly targeted at professional applications, can also be used for broadcasting, but these require a higher level of available C/N and the adoption of advanced pre-distortion methods in the uplink station to minimise the effect of transponder non-linearity.

Whilst these modes are not as power-efficient as the other modes, the spectrum efficiency is much greater. The 16APSK and 32APSK constellations have been optimized to operate over a non-linear transponder by placing the points on circles. Nevertheless their performance on a linear channel are comparable with those of 16QAM and 32QAM, respectively.

By selecting the modulation constellation and code rates, spectrum efficiencies from 0.5 to 4.5 bit/symbol are available and can be chosen dependant on the capabilities and restrictions of the satellite transponder used.

DVB-S2 has three roll-off factor choices to determine spectrum shape: 0.35 as in DVB-S, 0.25 and 0.20 for tighter bandwidth restrictions.

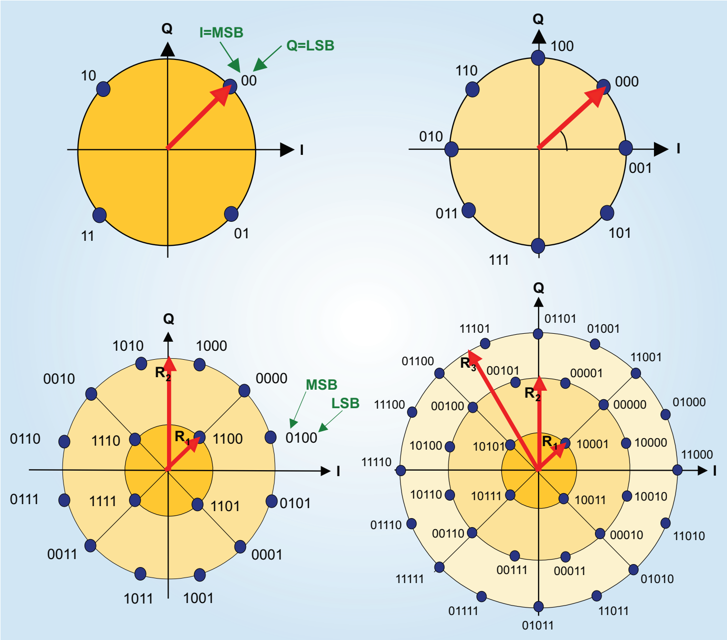

Fig. 2.2 DVB-S2 modulations: QPSK - 8PSK - 16APSK - 32APSK

2.1.2 Framing

In the DVB-S2 standard, two framing structures are designed:

- the *Base-Band* (BB) frames, carrying a variety of signalling bits in order to allow maximum flexibility on the input signal adaptation;
- the *Physical Layer* (PL) frames, carrying few highly-protected signalling bits.

The *Base-Band* framing structure allows a complete signalling functionality to configure the receiver according to the application scenarios: single or multiple input streams, generic or transport stream, CCM or ACM. Thanks to the protection performed by the concatenation of the BCH and LDPC codes and the wide length of the FEC frame, the BB-Header may contain many signalling bits (80) without loosing neither transmission efficiency nor ruggedness against noise. This BB-Header carries other important signalling information, such as: labelling the modulator input streams, describing the position and characteristics of user packets, indicating the presence of padding bits in the transmitted baseband frame, signalling the activation of specific tools (Null-packet deletion function, Input Stream Synchronization function, etc.), signalling the adopted modulation roll-off, [6].

The *Physical Layer* framing structure, instead, provides robust synchronization and signalling at Physical layer. Thus, a receiver may synchronise (carrier and phase re-

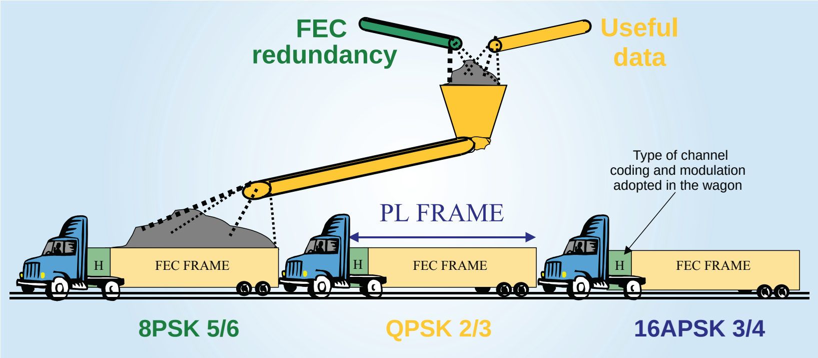

Fig. 2.3 PL framing structure with the ACM adoption

covery, frame synchronization) and detect the modulation and coding parameters before demodulation and FEC decoding. As shown in Fig. 2.3, the DVB-S2 Physical Layer is like a "train" composed of a regular sequence of periodic "wagons" (Physical Layer frames, PL Frame). Within a wagon, the modulation and coding scheme is homogeneous, but may change (if the Adaptive Coding and Modulation scheme is adopted) in adjacent wagons.
Every PL Frame is composed of:

- a payload composed by a Normal or a Short FEC frame;
- a PL-Header, containing synchronization and signalling information: type of modulation and FEC rate, frame length, presence/absence of pilot symbols to facilitate synchronization.

The PL-Header is always composed of 90 symbols and the payload is always composed of an integer multiple of 90 symbols (excluding pilot symbols). Since the PL-Header is the first entity to be decoded by the receiver, it could not be protected by the powerful FEC scheme. On the other hand, it had to be perfectly decodable under the worst-case link conditions. Therefore, designers have selected a very low-rate $7/64$ block code, suitable for soft-decision correlation decoding, and have minimised the number of signalling bits to reduce decoding complexity and global efficiency loss.

2.1.3 Adaptive Coding and Modulation

The *Adaptive Coding and Modulation* (ACM) functionality allows the use and the change of different modulation formats and error protection levels (i.e. different coding rates) on a frame-by-frame basis within the transmitted data stream, as already shown in Fig.2.3. By means of a return channel, informing the transmitter of the actual receiving conditions, the transmission parameters may be optimized for each individual user, dependant on path conditions.

Thus, ACM is considered a powerful tool to further increase system capacity, allowing for better utilisation of transponder resources. As a consequence, in DVB-S2 standard ACM is included as normative for the interactive applications and optional for DSNG and professional services.

The physical layer adaptivity is achieved through the following steps:

- Via a return channel, Satellite Terminals (ST) provide to the Gateway (GW) information on the channel status, by signalling the SINR and the most efficient modulation and coding scheme the ST can support. As periodic reports increase the signalling overhead on the return link, a preferable approach would be the ST sending a message whenever channel variations imply a change in the spectral efficiency.
- The ST indications are taken into account by the GW in coding and modulating the data packets addressed to each ST. Therefore service continuity is achieved, during rain fades, by reducing user bits while increasing at the same time FEC redundancy and/or modulation ruggedness. On the contrary, during the more frequent clear sky periods a much higher information rate can be delivered to the ST thanks to a higher spectral efficient physical layer mode.
- In order to avoid information overflow during fades, a source bit rate control mechanism has to be implemented, adapting the offered traffic to the available channel capacity.

The ACM gain increases for critical propagation conditions; therefore ACM is fundamental, in particular, for the higher frequency bands (e.g. *Ka* band) and for tropical climatic zones.

A crucial issue in ACM systems is the physical layer "adaptation loop delay", as it is strictly linked to the system capability of tracking channel variations. The adaptation loop can be defined as the set of operations, which occur starting from channel estimation at the STs ending with reception of the information encoded/modulated according to the reported channel status. Hence, the adaptation loop delay is a sum of several contributions, including: the delay for transmission of the channel status reports, the return link propagation delay (depending on the selected return channel), the delay introduced within the GW (buffering, processing and transmission of data packets), and finally the fixed 250 ms propagation delay on the forward link. Whenever the user link is degraded in such a way that it requires a protection level higher than the estimated one, the received packet cannot be correctly decoded. On the contrary, if the channel conditions have improved so that a higher efficient physical layer mode could be supported, the result is a loss in efficiency due to the utilisation of a not optimum physical layer scheme (i.e. carrying too much code redundancy). Therefore, the longer the loop delay the higher the impact physical layer adaptation has on user QoS, because of propagation channel dynamic.

On the other hand, if the adaptation loop is fast, service continuity may be guaranteed even during fast rain fades while, at the same time, keeping low C/N transmission margins to maximise the overall system throughput. Since maximum $C/N+I$ variation rates at Ka band have been estimated to be of about 0.5 dB per second during heavy rain fades, [23], and since the C/N distance between two adjacent DVB-S2 protection levels is around 1 dB, loop delays smaller than 1 second should allow minimisation of transmission packet losses.

2.1.4 Generic Stream Encapsulation

The *Generic Stream Encapsulation* (GSE) protocol, [21]-[22], is devised as an adaptation layer able to provide network layer packet encapsulation and fragmentation functions over Generic Stream. GSE provides an efficient encapsulation of IP datagrams over variable length Layer 2 packets, which are, then, directly scheduled on the physical layer into Base Band frames.

GSE maximises the efficiency of IP datagrams transport reducing the overhead by a factor 2 to 3 with respect to MPE over MPEG-TS. This is achieved without any compromise of the functionalities provided by the protocol, due to the variable length Layer 2 packet size, suited to IP traffic characteristics. For example in an interactive DVB-S2 system, the overhead is reduced on average from about 10% for MPE/MPEG-TS to 2% to 3% for GSE. Hence, yielding an overall throughput gain of about 5% to 15%, the actual benefit is of course dependent on the concrete system and traffic characteristics.

In addition to the overhead reduction, GSE provides a more efficient system operation for interactive systems that utilise advanced physical layer techniques such as Adaptive Coding and Modulation one. The inherent channel rate variability experienced in ACM systems makes the Generic Stream format more suited than the Transport Stream. GSE provides a flexible fragmentation and encapsulation method, which permits use of a “smart” scheduler to optimise system performance, either by increasing the total throughput and/or by improving the average packet end-to-end delay. In addition, GSE flexibility leads to a reduction in packet loss under fading variations, allowing the scheduler at the transmitter to dynamically change transmission parameters (e.g. modulation scheme and coding rate) for a particular network layer packet.

GSE also provides additional features that increase the protocol flexibility and applicability. Some key functions of this protocol are:

1. Support for multi-protocol encapsulation (IPv4, IPv6, MPEG, ATM, Ethernet, etc.).
2. Transparency to network layer functions, including IP encryption and IP header compression.

3. Support of several addressing modes: besides the 6-byte MAC address (including multicast and unicast), it supports a MAC addressless mode and a optional 3-byte address mode.
4. A mechanism for fragmenting IP datagrams or other network layer packets over Base Band frames to support ACM/VCM.
5. Support for hardware filtering.
6. Extensibility: additional link protocols can be included through specific protocol type values (e.g. Layer 2 security, IP Header Compression, etc.).
7. Low complexity.

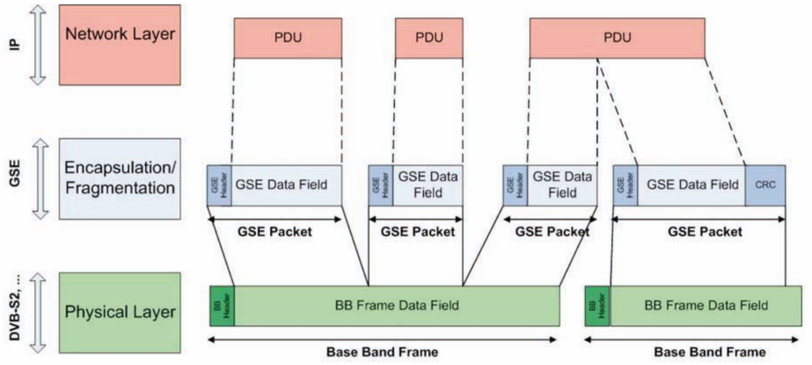

Fig. 2.4 GSE encapsulation within DVB-S2 stack

Fig. 2.4 summarises how the encapsulation scheme works in the DVB-S2 system. Protocol Data Units (PDUs) (e.g. IP packets), scheduled for transmission, are encapsulated in one or more GSE Packets. The encapsulation process delineates the start and the end of each network-layer PDU, adds control information such as the network protocol type and address label, and provides an overall integrity check when needed. The PDU can be encapsulated in a single GSE Packet or sliced into PDU fragments and encapsulated in several GSE Packets. GSE Packets have, in general, variable length, in order to match the input IP traffic with minimum overhead. GSE Packets can be sent in different Base Band frames, not necessarily consecutive or with the same transmission parameters (modulation scheme, coding rate). A Base Band frame can, therefore, multiplex more than a single GSE Packet.

In an ACM system, transmission parameters typically change dynamically on a frame-by-frame basis. GSE protocol requires that a Base Band frame always starts with the GSE Header of the first GSE Packet. GSE Packet fragmentation between Base Band Frames is, therefore, not allowed. In this case, a scheduler in the GSE encapsulator, which performs a "smart" placement of GSE Packets in the Base Band frames, can allow for optimizing system efficiency. In particular, a joint operation of scheduling and encapsulation can eliminate link efficiency losses and can achieve a better system efficiency.

2.1.5 *Backwards-compatible modes*

The large number of DVB-S receivers already installed, makes it very difficult for many established broadcasters to think of a new change of technology in favour of DVB-S2. In such scenarios, backwards-compatibility has been required in the migration period, in order to allow legacy DVB-S receivers to continue operating, while providing additional capacity and services to the advanced receivers. At the end of the migration process, when the complete receiver population has migrated to DVB-S2, the transmitted signal could be modified to the non-backward compatible mode, thus exploiting the full potential of DVB-S2.

Therefore, optional backwards-compatible (BC) modes have been defined in DVB-S2, intended to send two Transport Streams on a single satellite channel. The first (High Priority, HP) stream is compatible with DVB-S receivers (according to [3]) as well as with DVB-S2 receivers, while the second (Low Priority, LP) stream is compatible with DVB-S2 receivers only.

Backwards compatibility can be implemented by hierarchical modulation, where the two HP and LP Transport Streams are synchronously combined at modulation symbol level on a non-uniform 8PSK constellation: the two HP DVB-S bits define a QPSK constellation point, while the single bit from the DVB-S2 encoder sets an additional rotation $\pm\theta$ before transmission. Since the resulting signal has a quasi-constant envelope, it can be transmitted on a single transponder driven near saturation.

2.2 The DVB-SH System

DVB-SH is the mobile broadcast standard, developed by the DVB Project starting from 2006 and designed to deliver video, audio and data services to small handheld devices such as mobile telephones, to vehicle-mounted devices, to nomadic (laptops, palmtops, etc.) and to stationary terminals, [9]-[10]-[11]. It is planned to use frequencies below 3 GHz, typically S band frequencies around 2.2 GHz adjacent to the 3G terrestrial frequencies.

The key feature of DVB-SH is that it is a hybrid satellite and terrestrial system that allows the use of a satellite to achieve coverage of large regions or even a whole country whereas, in areas where direct reception of the satellite signal is impaired, and for indoor reception, terrestrial repeaters are used to improve service availability.

The DVB-SH standard provides a universal coverage by combining a Satellite Compo-

nent (SC) and a Complementary Ground Component (CGC); in a cooperative mode, the SC ensures geographical global coverage while the CGC provides cellular-type coverage. All types of environment (outdoor, indoor) can then be served, either using the SC from its first day of service, and/or the CCG that is to be progressively deployed, building on the success of DVB-H, [24].
A typical DVB-SH system is based on a hybrid architecture combining a SC and, where necessary, a CGC consisting of terrestrial repeaters fed by a broadcast distribution network (DVB-S2, fibre, xDSL, etc.), as it is shown in Fig. 2.5. The repeaters may be of three kinds:

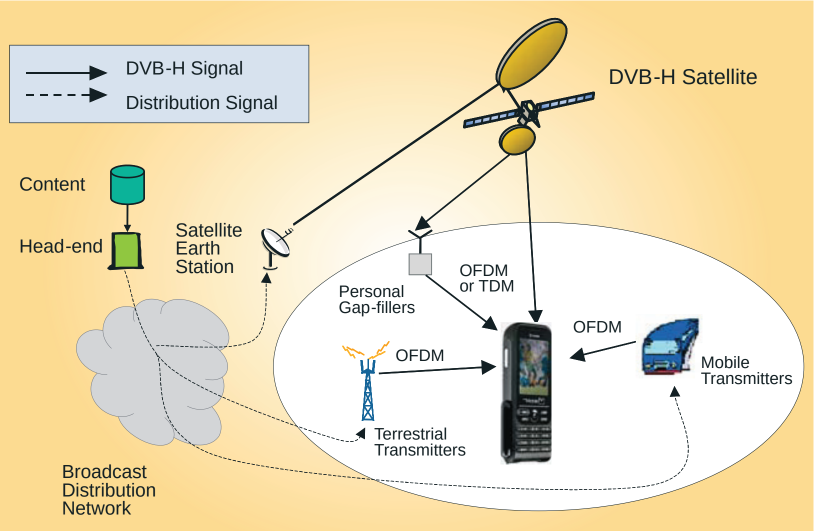

Fig. 2.5 DVB-SH general system architecture

- *Terrestrial Transmitters*: they are broadcast infrastructure transmitters, which complement the signal reception in areas where satellite reception is difficult, like in urban areas; they can be co-located with mobile cell sites or standalone.
- *Personal Gap-fillers*: they have limited coverage, providing local on-frequency retransmission and/or frequency conversion; a typical application is indoor enhancement of satellite coverage.
- *Mobile transmitters*: they are mobile broadcast infrastructure transmitters creating a “moving complementary infrastructure”. Typical use is for trains, commercial ships or other environments where continuity of satellite and terrestrial reception is not guaranteed by the fixed infrastructure.

The main innovative issues introduced by DVB-SH are the following:

- seamless service continuity between SC and CGC coverages;

- support of all reception conditions associated to portable and mobile terminals: indoor/outdoor, urban/suburban/rural, static/mobile conditions. Typical mobility conditions covers pedestrian as well as land vehicular scenarios;
- possible implementation of power saving schemes to minimise the power consumption of battery activated terminals in order to maximise autonomy;
- local insertion of broadcast services on CGC;
- use different kinds of distribution network to feed the CGC repeaters, such as Satellite (DVB-S/S2) and/or terrestrial (Optical fibre, Wireless Local Loop, xDSL, etc.) resources;
- possible offering of interactive services by inter-working with mobile or wireless systems at service, network head-ends and user terminal levels.

2.2.1 Architectures

The DVB-SH system includes two transmission modes:

1. **SH-A architecture**: it exploits OFDM transmission mode for both SC and CGC. SH-A allows a Single Frequency Network (SFN) between the SC signal and the CGC signal carrying the same content. If SFN is implemented, FEC, channel interleaver, modulation and guard interval cannot be optimized separately for the SC and CGC (by definition of SFN). If it is desirable to optimise these parameters separately for the SC and the CGC, a distinct frequency channel for the SC and the CGC can also be used in SH-A, leading to reduced spectrum efficiency and some handover complications for receivers having only one RF front-end.
2. **SH-B architecture**: it exploits TDM transmission mode for the SC and OFDM transmission mode for the CGC.
   SH-B requires a distinct frequency band for the SC and the CGC since they transmit signals based on two different physical layers. Each component of the transmission system can be optimized separately to its respective transmission path.

In the case of a single-carrier per HPA payload configuration, exploitation of the SH-B (TDM) configuration reduces the signal envelope peak-to-average factor, thus allowing HPA optimum operation close to its saturated power. SH-A is, instead, penalised by its intrinsic multi-carrier (OFDM) signal nature that requires a higher optimum HPA back-off. However, in the case of a multi-carrier onboard HPA operation, there is little or no difference between the performances obtainable with the SH-A or SH-B configurations.

In summary, SH-A requires satellite transponders operated in a quasi-linear mode, whereas SH-B targets satellite transponders operated at full saturation.

2.2.2 Receiver classes

A typical phenomenon of satellite reception with mobile terminals is long interruptions to the LOS conditions, resulting from the critical characteristics of satellite mobile channel due to the shading effects of buildings and bridges. Depending on the manner in which they cope with such interruptions, two types of receivers have been identified:

- The *Class 1 Receiver*: it is able to cope with rather short interruptions and mobile channel fading using appropriate mechanisms on the physical layer but supports the handling of long interruptions using redundancy on the link layer.
- The *Class 2 Receiver*: it is able to handle long interruptions (around 10 seconds) directly on the Physical Layer. This is made possible via the use of a large memory, directly accessible to the receiver chip.

It is up to the service and network operators to allocate the protection between the different layers, depending on the targeted quality of service, service categories and commercialised classes of receivers.

2.2.3 Physical layer

A functional description of the components required on the transmitter side is provided in Fig. 2.6. It can be seen that there is a common part including forward error correction and interleaving, which could be called *Outer Physical Layer* (OPL). A subset of 3GPP2 turbo code has been selected as FEC scheme while, as channel interleaver, a flexible scheme has been chosen in order to offer time diversity from about one hundred milliseconds to several seconds, depending on the targeted service level and corresponding capabilities (essentially memory size) of the terminal class.
Then, there are two different *Inner Physical Layers* (IPLs):

1. IPL-OFDM: Inner Physical Layer with multi-carrier modulation (OFDM).
   The multi-carrier modulation concept is derived from DVB-T;
2. IPL-TDM: Inner Physical Layer with single-carrier modulation (TDM).
   The single-carrier modulation concept is adapted from DVB-S2 technology.

Hence, for the OFDM part, the possible choices, as what concerns the modulation scheme, are QPSK, 16QAM and non-uniform 16QAM with support for hierarchical modulation. Moreover, a $1K$ mode, which does not exist in either DVB-T or DVB-H systems, has been proposed in addition to the usual $2K$, $4K$ and $8K$ modes. The $1K$ mode targets mainly L band where the planned channel bandwidth is 1.75 MHz.
For the TDM part, instead, the choices are QPSK, 8PSK, 16APSK for power and

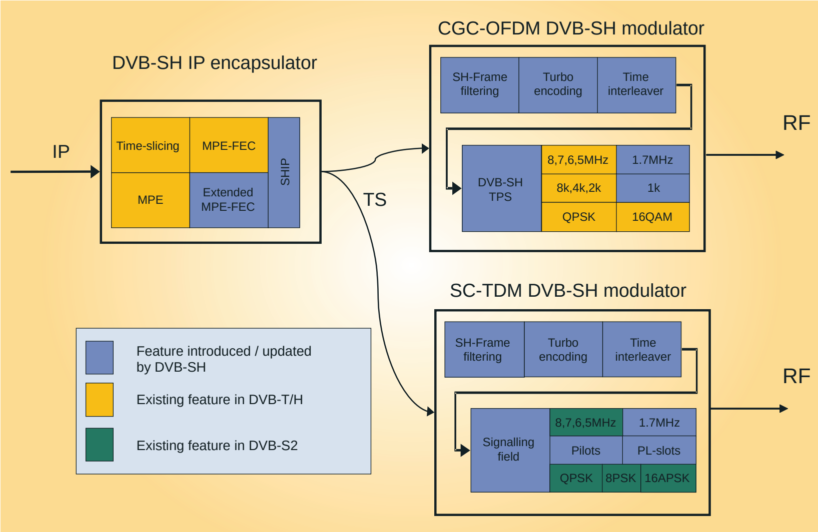

Fig. 2.6 Functional blocks of the DVB-SH transmitter

spectral-efficient modulation formats, with a variety of roll-off factors (0.15, 0.25, 0.35), as it is expected in the DVB-S2 standard.

2.2.4 Link layer

The Link layer features of the DVB-SH are, mainly, inherited from DVB-H and they can be summarised as follows:

- support of MPEG2-TS packets at the input, although the specification allows for the introduction of a Generic Stream, as well;
- MPE encapsulation and support of MPE Time Slicing (power-saving) and handover between frequencies/coverage beams;
- compatibility with MPE-FEC (intra-burst FEC);
- GSE ready.

However, the longer fading experienced in the satellite context, tends to require longer protection than provided by MPE-FEC. Therefore, a MPE-FEC extension (MPE-IFEC) has been introduced in the system. This MPE-FEC extension is expected to combat the deep and long shadowing encountered in some satellite channels by providing additional time diversity.

Finally, DVB-SH signalling is done via either TPS bits (OFDM part), or a header Signalling Field (TDM part). They allow the various parameters of both components to be controlled and can be made complementary, in particular when common operation of both different components is required in the SH-B architecture.

Chapter 3
New Interactive Satellite Systems

Abstract This chapter reports the analysis of the three current major trends worldwide in satellite communications concerning interactive and broadband applications: the DVB-RCS standard for the return channel via satellite, the Internet Protocol over Satellite (IPoS) standard and the *SurfBeam* system. Furthermore, some details about the extension of the DVB-RCS standard for the usage in mobile environments, are provided. The revision 1.5.1 of DVB-RCS, also known as DVB-RCS+M standard, includes new features to accommodate the challenges of the mobile satellite link and to meet regulatory constraints for mobile services.

3.1 The DVB-RCS System

DVB-RCS is a technical standard, developed by the DVB Project starting from 1998, that defines a complete air interface specification for two-way satellite broadband VSAT (Very Small Aperture Terminal) systems, [7]-[8]. Low cost VSAT equipment can provide highly dynamic, demand-assigned transmission capacity to residential and commercial/institutional users. DVB-RCS provides users with the equivalent of an ADSL or cable Internet connection, without the need for local terrestrial infrastructure.

DVB-RCS was developed in response to a request from several satellite and network operators who wanted to embark on large-scale deployment of such systems considering it essential to have an open standard in order to mitigate the risks associated with being tied to a single vendor. The standard was developed using state-of-the art techniques, allowing an optimised trade-off between performance and cost, [25].

3.1.1 Reference System Model

A generic reference system model for interactive systems is shown in Fig. 3.1, [7]. In the model, two channels are established between the service provider and the user:

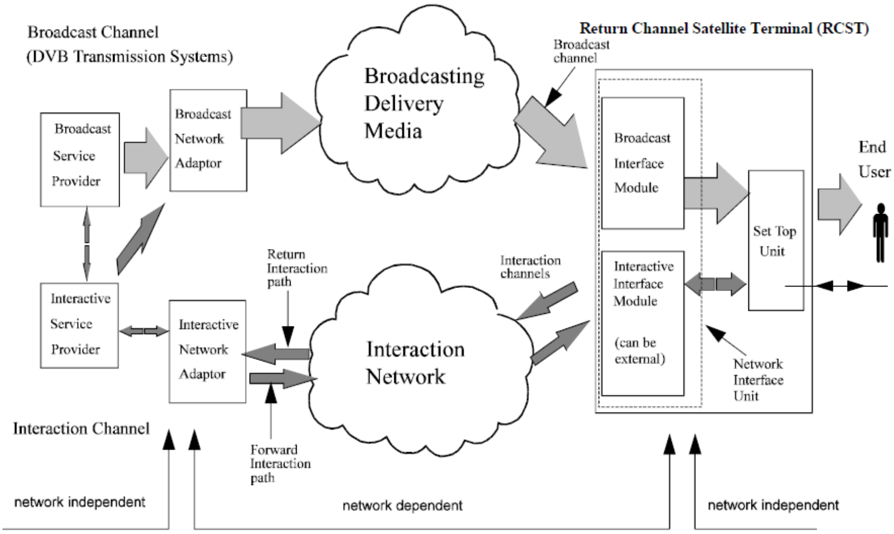

Fig. 3.1 DVB reference system model for interactive systems

- *Broadcast Channel*: a unidirectional broadband Broadcast Channel including video, audio and data is established from the service provider to the users. It may include the Forward Interaction Path.
- *Interaction Channel*: a bi-directional Interaction Channel is established between the service provider/user and the user for interaction purposes. It is, in turn, formed by:
    - *Return Interaction Path (Return Channel)*: from the user to the service provider. It is used to make requests to the service provider/user, to answer questions or to transfer data.
    - *Forward Interaction Path*: from the service provider to the user. It is used to provide information from the service provider/user to the user(s) and any other required communication for the interactive service provision. It may be embedded into the Broadcast Channel. It is possible that this channel is not required in some simple implementations which make use of the Broadcast Channel for the carriage of data to the user.

Fig. 3.2 shows the different entities which compose an interactive satellite system. In

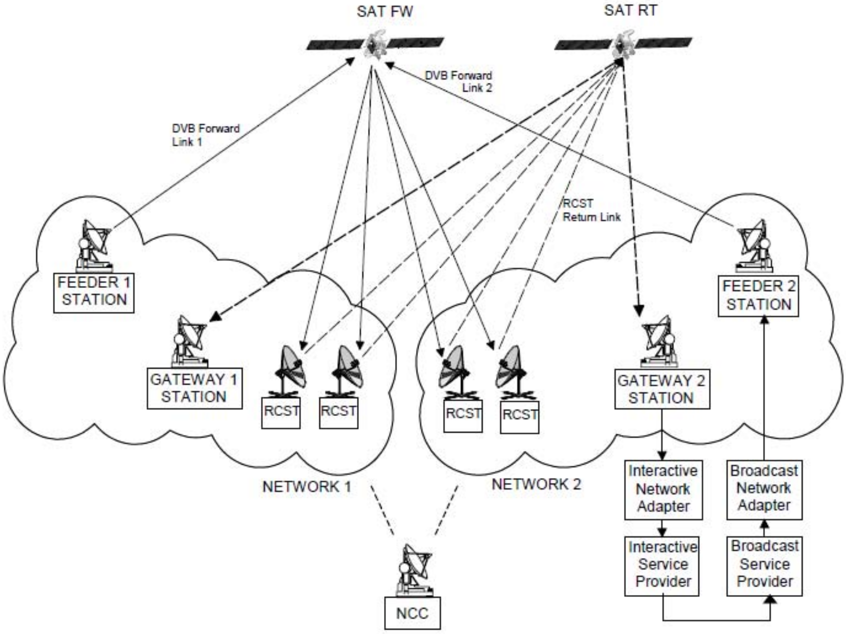

Fig. 3.2 Interactive system network components

particular, the main elements are:

- **The Return Channel Satellite Terminal** (RCST): a RCST is formed by the Network Interface Unit (consisting of the Broadcast Interface Module and the Interactive Interface Module) and the Set Top Unit. The RCST provides interface for both Broadcast and Interaction Channels. The interface between the RCST and the interaction network is via the Interactive Interface Module.
- **Network Control Centre** (NCC): a NCC provides Control and Monitoring Functions. It generates control and timing signals for the operation of the Satellite Interactive Network to be transmitted by one or several Feeder Stations.
- **Traffic Gateway** (TG): a TG receives the RCST return signals, provides accounting functions, interactive services and/or connections to external public, proprietary and private service providers (data bases, pay-per-view TV or video sources, software download, tele-shopping, tele-banking, financial services, stock market access, interactive games etc.) and networks (Internet, PSTN, etc.).
- **Feeder**: a Feeder transmits the forward link signal, which is a standard satellite digital video broadcast (DVB-S or DVB-S2) uplink, onto which are multiplexed the user data and/or the control and timing signals needed for the operation of the Satellite Interactive Network.

3.1.2 Forward link

The forward link carries signalling from the NCC and user traffic to RCSTs. The signalling from the NCC to RCSTs that is necessary to operate the return link system is called "Forward Link Signalling". Both the user traffic and forward link signalling can be carried over different forward link signals. Several RCST configurations are possible depending on the number of forward link receivers present on the RCST.
The forward link signal received by RCSTs is based on DVB-S or DVB-S2 specifications, [3]-[5]. If the DVB-S2 standard is considered, both the broadcast profile using only Constant Coding and Modulation and the interactive profile using adaptive coding and modulation can be used.

3.1.3 Return Link

3.1.3.1 Burst formats

In the DVB-RCS system there are four types of burst format, [7]:

- **TRaFfic (TRF) bursts**: they are used for carrying useful data from the RCST to the Gateway/RCST. The data to be transported can be encapsulated in Asynchronous Transfer Mode (ATM) cells, using ATM Adaption Layer 5 (AAL-5), or use a native IP encapsulation over MPEG2-TS packets.
- **ACQuisition (ACQ)** and **SYNChronisation (SYNC) bursts**: they are required to accurately position RCST burst transmissions during and after logon procedure. An ACQ burst can be used to achieve synchronisation, prior to operational use of the network by the RCST. A SYNC burst is used by a RCST for the purpose of maintaining synchronisation and sending control information to the system.
- **Common signalling channel (CSC) bursts**: they are only used by an RCST to identify itself during logon. They are composed of a preamble for burst detection and start of burst detection, a field describing the RCST capabilities, the RCST MAC address CSC_Route_ID, Dynamic Connectivity, Frequency Hopping, reserved field and a burst type identifier.

3.1.3.2 Channel Coding and Modulation

Channel Coding techniques are applied to traffic and control data, which are transmitted in the types of bursts described in the previous subsection. Two coding schemes are possible:

1. Turbo coding;

2. Concatenated coding.

RCSTs implement both schemes. Within a session RCSTs are not requested to change the coding scheme (i.e. during a given session, a RCST either use the Turbo codes or the concatenated code). In the case of the concatenated coding, the outer code is a by-passable Reed-Solomon (RS) code and the inner code is a by-passable non-systematic convolutional code according to [3]. For both coding schemes, a by-passable Cyclic Redundancy Code (CRC) can also be applied on CSC and SYNC bursts in order to allow error detection.

In the concatenated coding, as outer code, a shortened Reed-Solomon scheme derived from the original RS (255, 239, 8) code, can be applied for some burst formats. The outer code can be bypassed and it is always by-passed when Turbo codes are used. As inner code, the system allows for a range of punctured convolutional codes, based on a rate $1/2$ mother convolutional code with constraint length $K = 7$ corresponding to 64 trellis states. Supported code rates are $1/2$, $2/3$, $3/4$, $5/6$ and $7/8$. Also the inner code can be bypassed and it is always by-passed when Turbo codes are used. The convolutional encoder register is initialised to all zeroes before encoding the first data bit. The Turbo encoder, instead, uses a double binary Circular Recursive Systematic Convolutional (CRSC) code, [26]-[27]. The permutation within the Turbo encoder is done on two levels: the first one *inside* the couples of systematic bits while the second one *between* couples of systematic bits. In this coding scheme, the adopted termination technique is called *tailbiting* or *circular termination* because it allows to view the code trellis as a circle, without any state discontinuity. Tailbiting enables to transform a convolutional code into a block code by allowing any state of the encoder to be the initial state and by encoding the sequence so that the final state of the encoder is equal to the initial state. Seven code rates are defined for the Turbo mode: $R = 1/3, 2/5, 1/2, 2/3, 3/4, 4/5, 6/7$. This is achieved through selectively deleting the parity bits (puncturing).

As what concerns the modulation scheme, instead, a conventional Gray-coded QPSK modulation with absolute mapping (no differential coding) has been selected. Prior to modulation, the in-phase and quadrature signals are square root raised cosine filtered.

3.1.3.3 Multiple Access

In order to achieve flexible and efficient use of satellite resources, DAMA (Demand Assigned Multiple Access) techniques are adopted in the system. The standard includes bandwidth-on-demand protocols which can mix constant-rate, dynamic-rate, volume-based and best-effort bandwidth allocation.

On the other hand, as satellite access scheme, a Multi-Frequency Time Division Multiple Access (MF-TDMA) has been selected. MF-TDMA allows a group of RCSTs to communicate with a TG using a set of carrier frequencies, each of which is divided into time-slots. The NCC allocates to each active RCST a series of bursts, each defined by a frequency, a bandwidth, a start time and a duration.

The MF-TDMA scheme can be either fixed-slot or dynamic-slot. In the fixed-slot MF-TDMA, the bandwidth and duration of successive traffic slots used by an RCST is fixed. On the other hand, dynamic-slot MF-TDMA uses additional RCST flexibility to vary the bandwidth and duration of successive slots allocated to a RCST, as shown in Fig. 3.3. In addition to changing carrier frequency and burst duration, the RCST can also change transmission rate and coding rate between successive bursts. The advantage of having a more flexible RCST is that of achieving a more efficient adaptation to the widely varying transmission requirements typical of multimedia services.

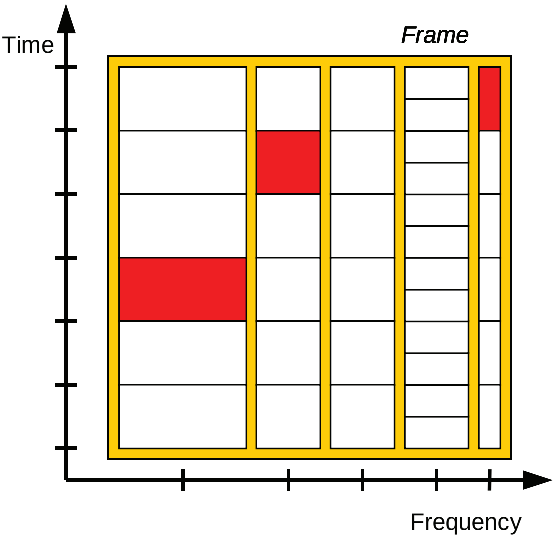

Fig. 3.3 Dynamic-slot MF-TDMA

In the MF-TDMA scheme the transmission is organised in superframes. The superframe duration is, usually, envisaged to be in the order of a few tens or hundreds of milliseconds. The time-frequency resources are so partitioned into superframes, a superframe into frames and a frame, in turn, into timeslots, as shown in Fig. 3.4. A Superframe_ID identifies the return link resources accessed by a given set of RCSTs. For each superframe (of a given Superframe_ID), allocation of timeslots is communicated to the RCSTs via the TBTP table. The RCST processes the TBTP message from the NCC for its allocation area, in order to extract the assignment count and timeslot allocations for its next uplink transmissions. The latency time from the arrival of the TBTP message at the RCST until the RCST is ready to transmit the bursts assigned by that TBTP, does not exceed 90 ms. A RCST is allowed to transmit bursts only in

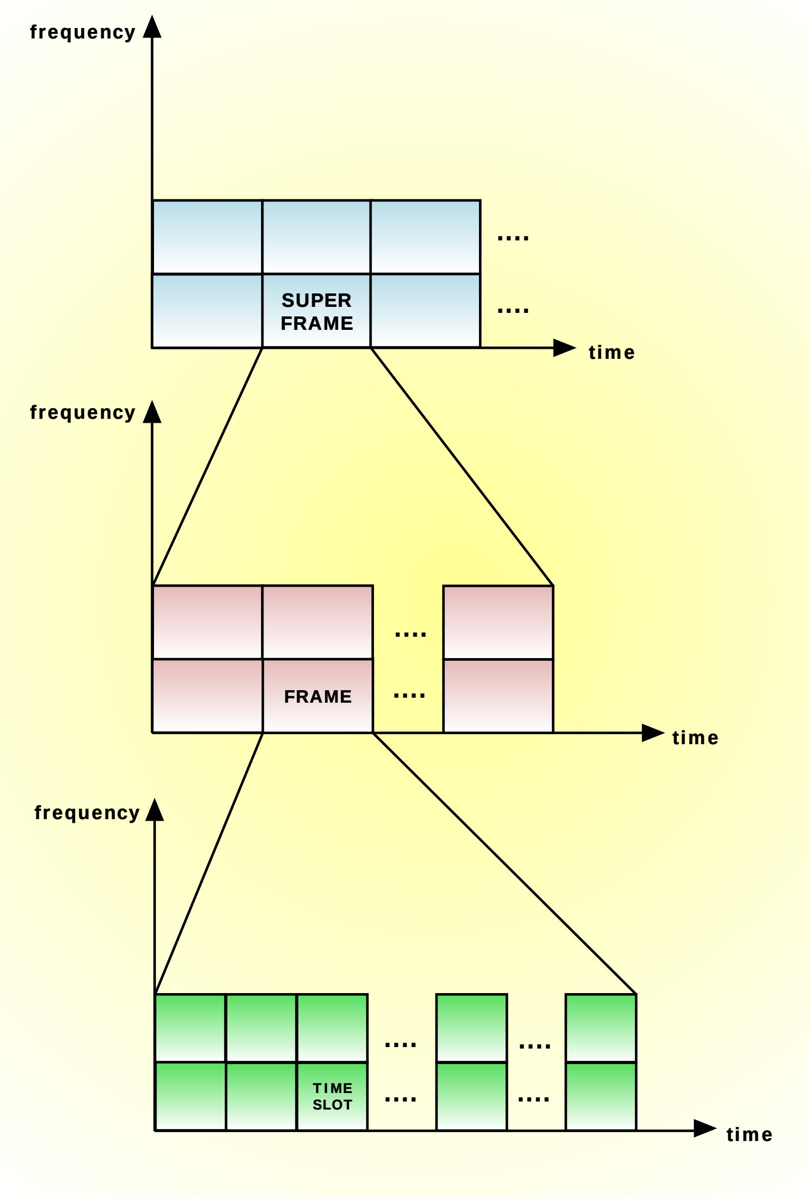

Fig. 3.4 Superframe structure in MF-TDMA scheme

timeslots which were allocated to it (“dedicated access”), or on random-access timeslots (“contention access”).

The frame is at an intermediate level between the superframe and the timeslots. It is introduced for reasons of signalling efficiency (on the forward link signalling). In a frame, timeslots are numbered from 0 (lowest frequency, first in time) to M (highest frequency, last in time), where M is less than or equal to 2047, and, then, ordered before in time and then in frequency. Frames and superframes can all have the same duration, in which case frames can be seen as frequency sub-bands of the superframe.

3.1.4 The SatLabs Group

The SatLabs Group is an international, not-for-profit association whose members are committed to bringing the deployment of the DVB-RCS standard to large-scale adoption, [16]. SatLabs membership is comprised of service providers, satellite operators, system integrators, terminal manufacturers and technology providers with an interest in DVB-RCS.

The main goal of the SatLabs Group is to ensure interoperability between DVB-RCS terminals and systems and to achieve low-cost solutions.

The work of the SatLabs Group falls into five domains:

- Interoperability - ensuring interoperability between DVB-RCS terminals and systems.
- Cost reduction - lowering user terminal and service provision costs.
- Availability - supporting DVB-RCS market development and definition of solutions for service and application support.
- DVB-RCS awareness - publishing information about DVB-RCS capabilities and implementation.
- Standard evolution - defining enhancements to cope with new user requirements or to increase service provision efficiency.

SatLabs Group operates a qualification laboratory, where terminals can be tested to prove their operation in accordance with the standard. Furthermore, SatLabs defines supplementary standards that build upon the solid foundation of DVB-RCS and offers conformance testing against these supplementary standards.

3.1.5 Market Deployment

Despite its non-dominant market position because of higher cost terminal price, DVB-RCS is still the most promising open standard. Many equipment manufacturers cur-

rently have developed or are in the process of developing DVB-RCS compliant equipment making it the most widely adopted standard in terms of manufacturer numbers.
By mid 2007, there had been more than 150 DVB-RCS systems deployed worldwide, serving around 100.000 terminals at Ku band, Ka band, C band and EHF, [25]. DVB-RCS is today the only multi-vendor VSAT standard. For this reason, it is often mandated in systems procurement by customers who wish to ensure that their choice of terminal vendor remains open after the initial procurement. The maturity and capability of DVB-RCS systems is also well recognised. DVB-RCS is clearly growing in many markets, with a greater variety of applications worldwide. A mandate by the Russian government and usage by the United States Department of Defense are clear indicators that the DVB-RCS standard is the solution for multi-vendor VSAT broadband services. There are several manufacturers of interoperable DVB-RCS hubs and terminals which are members of the SatLabs Group.
Applications served by DVB-RCS systems are many and varied; typical primary uses include voice over IP services and general Internet access in rural areas, tele-medicine, tele-education and tele-government, as well as more conventional and generic Internet access services (e-mail, web browsing, etc.).

3.1.6 DVB-RCS Next Generation

In 2008, the DVB Project has initiated a major revision of the DVB - Return Channel Satellite (DVB-RCS) standard, [4]. In early 2009, the DVB Technical Module has approved the release of a Call for Technologies for *Next Generation DVB-RCS* (DVB-RCS NG). The Call for Technologies has required the submission of candidate technologies that could be considered for all or part of a standard for a future DVB interactive satellite communications system. The IP-based broadcast technology founded communications system, currently with the working name of DVB-RCS NG, will consist of:

- A specification for an interaction channel for satellite distribution systems (DVB-RCS 2*nd* Generation), basically seen as an upgrade to DVB-RCS (1*st* Generation) physical layer, MAC layer and IP packet encapsulation.
- An extended specification beyond the scope of DVB-RCS (1*st* Generation) for the required support of commonly used IP based protocols and applications (Higher Layer Satellite, HLS), providing interoperability and increasing the performance.

This call for technologies has been issued to meet the commercial requirements prepared by the DVB Commercial Module for Next Generation RCS.
It is expected that first specifications covering the most widespread star network configuration for fixed terminals will be agreed by the end 2009.

3.2 The IP over Satellite (IPoS) System

The Internet Protocol over Satellite (IPoS), [28], is a broadband satellite system developed by Hughes Network System and published as open standard by the TIA, ETSI, and ITU standards organisations. In more detail, it was ratified as a U.S. Telecommunications Industry Association standard (TIA-1008) in November 2003.
Such a standard fully specifies the layered architecture and protocols for the transmission of IP packets between a central hub station and remote satellite terminals using standard *Ku* band bent-pipe geosynchronous satellites. The IPoS system delivers "always on" IP services and is targeted at residential and enterprise markets. The primary services offered to these segments are broadband Internet access (for enabling applications such as e-mail, Web browsing and file transfer) and Wide Area Networking. Additionally, IP Multicast services such as audio/video streaming and distance learning can be offered through the IPoS system.
The IPoS standard applies to star satellite access networks wherein multiple remote terminals communicate bi-directionally with a hub as illustrated in the following Fig. 3.5, directly taken from [28]. Three major segments are included in the access network:

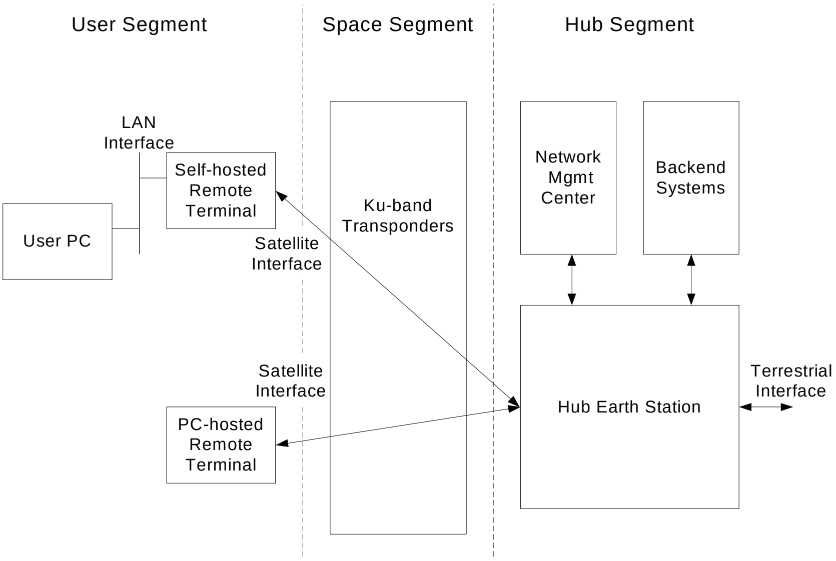

Fig. 3.5 IPoS system architecture

- *Hub segment*: It consists of the gateway interconnecting the satellite access network with the external networks, e.g. Internet, corporate or private packet networks. Typically, the gateway consists of a large earth station through which hundreds of thousands of satellite users communicate over a multiplicity of transponders over one or more satellites. The gateway is responsible for aggregating the traffic from remote users connecting to public and/or private data networks, converting traffic from one protocol to another, routing of the traffic across the satellite network and the overall management, configuration, and provisioning of the satellite access network.

- *Space segment*: It typically consists of commercial *Ku* band, bent-pipe transponders on geosynchronous satellites, allowing transmission in both directions between the hub and remote terminals. The IPoS physical layer interface assumes Ku-band commercial satellites with spectrum that is designated for Fixed Satellite Services (FSSs). The gateway may access space segment resources from multiple satellites.
- *User segment*: It is responsible for interfacing the user hosts or Personal Computers running the user applications at the customer premises. In general, the user segment consists of thousands to hundreds of thousands of remote terminals, each of them capable of providing broadband IP communications to a remote site through their IPoS satellite interface to the gateway.

The IPoS protocol is structured according to the ETSI Broadband Satellite Multimedia (BSM) protocol architecture as defined in [29]. This architecture provides a split between satellite-dependent and satellite-independent functions, through the Satellite-Independent Service Access Point (SI-SAP) interface, as illustrated in Fig. 3.6. This

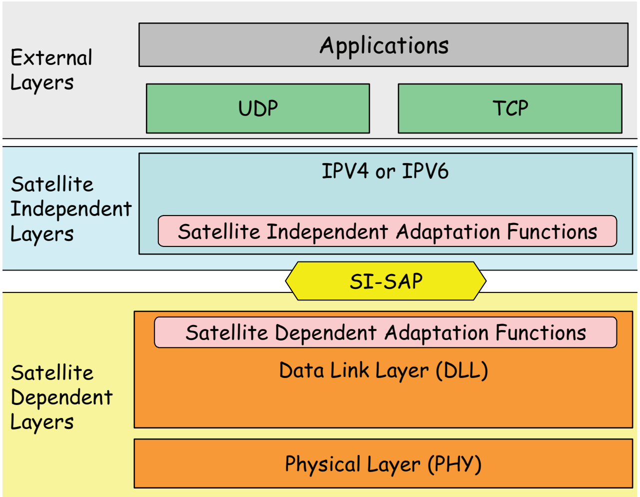

Fig. 3.6 IPoS protocol stack

standardized access point allows hardware and software which have been built to conform to the IPoS standard, to operate with any satellite-independent hardware and software that follows this interface specification, as well.

In the framework of the effective design and realisation of IPoS based terminals, the SI-SAP interface provides the following benefits: the separation of the satellite-specific aspects from the satellite-independent higher layers facilitates future developments in IP-based networking features to be easily accommodated within an IPoS terminal.

Besides, according to Hughes' achievements, [28], the SI-SAP interface used in IPoS is significant because it permits independent developments to occur in parallel, thereby improving terminals and systems as a whole to the benefit of all concerned parties.

The last condition is the background for the necessity of a SI-SAP emulator system suited to be employed as test-bed for future developments of the SI-SAP features in real, modern and efficient STs where IPoS is jointly employed with DVB-RCS/S2 satellite dependent layers.

3.3 The *SurfBeam* System

SurfBeam, developed by ViaSat Inc., is a broadband satellite system based on the Data Over Cable Service Interface Specification (DOCSIS), [30]-[31]. *SurfBeam* system is designed for the use with geostationary spot-beam based satellites in Ka (20/30 GHz) band and provides the user with a broadband access comparable to that currently offered by terrestrial service providers.

In particular, *SurfBeam* uses DOCSIS over Satellite (DOCSIS-S) standard which adapts the cable modem networking standard to satellite transmission. Because the DOCSIS broadband networking standard is already used by millions of terrestrial cable customers, the technology is highly developed and low-cost in terms of modem chipsets, hub (head end) hardware, installation and customer support. Specifically the only implementation of DOCSIS-S suggests that the Cable Modem Termination System could be substituted with an Equivalent Satellite Modem Termination System.

However, although the upper layer protocols are all based on the standard DOCSIS, the physical layer (PHY) has been modified to accommodate the unique challenges of the satellite-land channel which can be affected by deep fading periods and it is, therefore, characterized by continuous occurrence of LOS and NLOS conditions. Hence, the modulation scheme used by user terminals on the return link back to the satellite, is QPSK with a FEC rate equal to $1/2$ or $3/4$, in order to provide a higher robustness to this critical link. The *SurfBeam* system architecture is shown in Fig. 3.7, [31]. The equipment consists of a satellite modem (SM) and a Outdoor Unit (ODU) comprising of a satellite dish antenna and a transceiver. The satellite modem is analogous to cable modems but, instead of a cabled connection to the gateway, *SurfBeam* uses a satellite to communicate with the gateway. On the gateway side of the network, the system

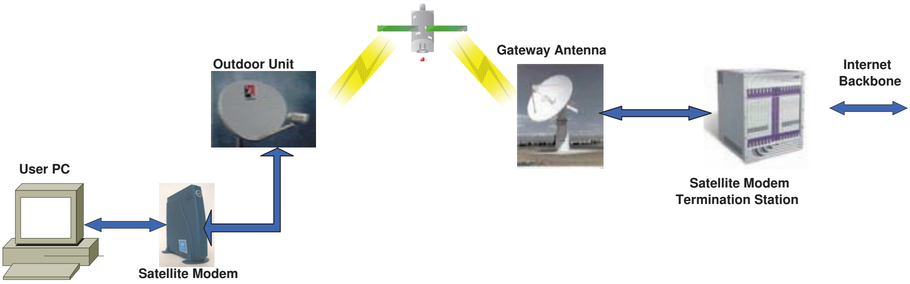

Fig. 3.7 *Surfbeam* system architecture

consists of a gateway antenna that connects to a Satellite Modem Termination System (SMTS) which, in turn, connects to the internet backbone.

3.4 A comparison of interactive satellite systems

This section aims at comparing and summarising the interactive satellite systems for fixed services, described in the previous sections: DVB-RCS, IPoS and *SurfBeam*. Table 3.1 reports the technical characteristics of the analysed satellite systems:

3.5 The DVB-RCS System for Mobile Environments

The revision 1.5.1 of DVB-RCS, also known as DVB-RCS+M standard, carried out in 2008 and published in January 2009, extends some DVB-RCS capabilities taking into account the support for mobile and nomadic terminals as well as enhanced support for direct terminal-to-terminal (mesh) connectivity, [12]. The considered terminals are, in the most of cases mounted on a mobile platform operating as a gathering point for multiple mobile users (trains, buses, ships, passengers' aircrafts) and, in a few cases, on top of cars or trucks that are serving one to a few mobile users only, [32].
DVB-RCS+M specification includes features such as live handovers between satellite spot-beams, spread-spectrum features to meet regulatory constraints for mobile terminals, and continuous carrier transmission mode for terminals with high traffic aggregation. It also includes link-layer forward error correction, used as a countermeasure against shadowing and blocking of the mobile satellite link, [25].

Satcom system comparison	**DVB-RCS**	**IPoS**	***SurfBeam***
Most typical implemented maximum data rates	Upstream: 144 kbps - 2048 kbps Downstream: DVB-S: 45/68 Mbps DVB-S2: 100+ Mbps	Upstream: 2048 kbps Downstream: DVB-S: 45/68 Mbps DVB-S2: 100+ Mbps	Upstream: 1203 (2406) kbps Downstream: 50 (108) Mbps
Modulation and Coding	Upstream: QPSK, Turbo codes or CC&RS many code rates Downstream: DVB-S2: QPSK, 8PSK, 16APSK, 32 APSK many code rates DVB-S: QPSK, CC&RS many code rates	Upstream: O-QPSK, Turbo codes or CC 1/2 Downstream: DVB-S2: QPSK, 8PSK, 16APSK, 32 APSK many code rates DVB-S: QPSK, CC&RS many code rates	Upstream: QPSK, Turbo codes 1/2 optional RS outer code Downstream: 8PSK, Turbo 2/3, 5/6 QPSK, Turbo 1/2, RS outer code
Adaptive Coding and Modulation	Yes Upstream: Adaptive coding Downstream DVB-S2: ACM	Yes Upstream: Adaptive coding and symbol rate Downstream DVB-S2: ACM	Yes some options
QoS Support	Yes	Yes	Yes
Frame formats	Upstream: MPEG or ATM cells Downstream: MPEG-TS DVB-S or DVB-S2 GS stream DVB-S2	Upstream: variable bursts Downstream: MPEG-TS DVB-S or DVB-S2 GS stream DVB-S2	Upstream: Header & Ethernet frame Downstream: MPEG-TS DVB-S or DVB-S2 GS stream DVB-S2
Advantages	OPEN standard, multiple vendor support compliance organization SatLabs	Standard with large number of terminals in operation, low cost	Works like a huge Ethernet, only one PID value necessary
Disadvantages	Terminals currently more expensive than DOCSIS-S because of volume of production	PROPRIETARY implementation, few vendors, no compliance organization	High uplink overhead for short IP datagrams, PROPRIETARY implementation, single vendor, no compliance organization
Applications	Two-Way Satellite Internet	Two-Way Satellite Internet	Two-Way Satellite Internet
Providers	Astra Broadband	Hughes	Wildblue-Eutelsat
Manufacturers	STM	Hughes	Viasat

Table 3.1 Comparison of interactive satellite systems

3.5.1 Reference System Model

A mobile satellite interactive network comprises the same functional blocks (e.g. NCC, GW, Interactive Network Adapter) and signalling mechanisms (forward and return link) as described for the DVB-RCS fixed scenario (for more details see Section 3.1). However, the mobile RCSTs, NCC and GW implement additional features (e.g. spreading, blocking channel countermeasures) which are specific to mobile environments. Mobility management mechanisms and techniques are included to address handover requirements in different application scenarios and environment conditions (LOS, NLOS). Moreover, specific signalling between NCC, gateway and RCSTs, to manage beam handovers, is introduced.

The reference model for this kind of scenario is shown in Fig. 3.8. The different mobile scenarios which are envisaged in a mobile DVB-RCS system can be classified as follows, [33]:

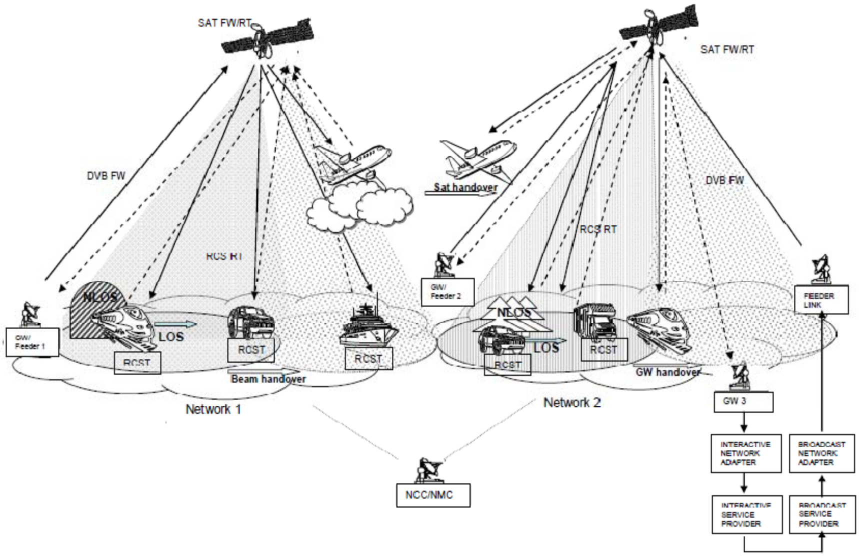

Fig. 3.8 Reference model for mobile satellite interactive systems

- **LOS scenarios**: these correspond to low-fading scenarios, which are almost always in LOS or close to LOS conditions. Aeronautical and maritime ones are the two main scenarios in this category:
  - *Maritime scenario*: this comprises, mainly, passenger transportation ships (e.g. cruises), commercial ships (e.g. cargos), and private transportation ships (e.g. sailing boats). Two coverage scenarios are particularly considered: a global one, corresponding to cruise routes (e.g. transatlantic cruises), and a regional one, corresponding to ferry routes (e.g. European coastal regions). Regarding the modelling of the LOS channel conditions encountered in the maritime scenario, considering the usage of high directive antennas, presence of a strong LOS can be assumed, and the channel can be modelled as a pure Ricean channel with a very high Rice factor, i.e. very close to a AWGN channel.
  - *Aeronautical scenario*: this comprises, mainly, passenger aircrafts (including wide-body and single aisle aircrafts) and private aircrafts (e.g. executive jets). Two coverage scenarios are particularly considered: a global one, corresponding to long- haul flights (e.g. transatlantic flights), and a regional one, corresponding

  to short and medium haul flights (e.g. over Europe). Regarding the modelling of the LOS channel conditions encountered in the aeronautical scenario, experimental results have shown that LOS conditions can be assumed and the channel can be fairly approximated by a AWGN channel for most of the time.

- **NLOS scenarios**: these correspond to land-based scenarios, where the LOS is frequently affected by frequent/deep/long signal blockages and shadowing. Railway and Land-vehicular are the two main scenarios in this category:
  - *Railway scenario*: this comprises, mainly, high-speed long-distance trains. Only the regional coverage scenario is considered since trains remain within one continent. The mobility effects, such as multipath, shadowing and blockage, encountered due to the local environment in the vicinity of the mobile RCST, such as adjacent buildings, vegetation, bridges, and tunnels, result in sporadic severe fading. Hence, the effect of deterministic and (space) periodic fades due to power arches are very relevant in this scenario. Regarding the modelling of the railway channel conditions, different propagation measurements at *Ku* and *Ka* bands have been performed in order to define reference statistical channel models:
    1. For *Ku* band, the behaviour of the land mobile satellite channel can be modelled using a 3-state (LOS, Shadowed and Blocked states) Markov chain model. The distributions which characterise each state, the transition matrix coefficients and the distribution parameters can be found in [34].
    2. For *Ka* band, the behaviour of the land mobile satellite channel can be modelled using a 3-state (LOS, Shadowed and Blocked states) Markov chain model. The distributions which characterise each state and the corresponding parameters can be found in [35]-[36].
  - *Land-Vehicular scenario*: this comprises, mainly, passenger vehicles (e.g. buses), commercial vehicles (e.g. trucks) and private vehicles (e.g. cars). Only the regional coverage scenario is considered since land-vehicles remain within one continent. Regarding the modelling of the channel conditions encountered in the land vehicular scenario, the same statistical channel models described above for the railway scenario apply here as well, [34]-[35]-[36].

In the following, the main additional features introduced in DVB-RCS+M will be taken into account. For further details about the DVR-RCS standard capabilities, refer to Section 3.1.

3.5.2 Forward Link

In case of mobile scenarios, the forward link signal received by RCSTs can be adapted to the mobile conditions by introducing some mobile functionalities. The main challenges that the mobile environment offers in the forward link consist in, mainly, signal blockage effects and possible interferences to and from adjacent systems, [32]. Thus some mitigation techniques need to be introduced.

3.5.2.1 Spectrum Spreading

In order to reduce interference coming from other systems, a DVB-S2 forward link transmission can be spread in bandwidth using the provisions adopted in [12]. A Direct Sequence (DS) spreading is applied in two stages: spreading and scrambling, as reported in Fig. 3.9. The first operation, spreading, multiplies every modulated symbol in PL frames of the DVB-S2 system, by a sequence of chips to enlarge the bandwidth of the signal. The second operation, scrambling, applies a scrambling code to spread the signal. Spreading factor values up to 4 are considered.

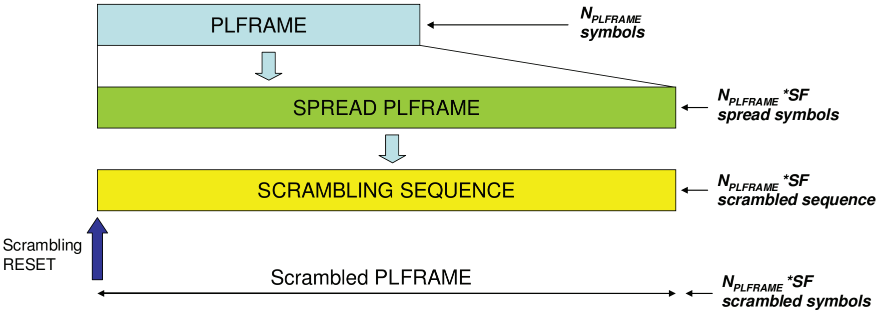

Fig. 3.9 Spectrum spreading in the foward link

3.5.2.2 Link Layer FEC

Traffic data can be further protected against channel impairments, through the inclusion and processing of additional coding scheme at link layer called Link Layer Forward Error Correction (LL-FEC). LL-FEC has been introduced in DVB-RCS+M to support reception in situations of high Packet Loss Ratio (PLR) at the MPE section or GSE packet level. Such high PLR can occur on mobile channels, for example, when the terminal speed is too high or when the signal-to-noise ratio is too low or the propagation results in fading. It can also occur due to obstruction, blockage or other situations in which the LOS condition is interrupted. With the LL-FEC, a variable amount of capacity is allocated to parity overhead.

Transmissions employing LL-FEC use the same basic data structures as other MPE/-GSE transmissions. The use of LL-FEC is optional and it is defined separately for each elementary stream in the transport stream or for each GSE-FEC stream in the generic stream. Each elementary or GSE-FEC stream can configure different code parameters, resulting in different delays, level of protection and FEC overhead.

LL-FEC can use the Raptor code as specified in [38] for LL-FEC frame ADT sizes up to 12 MBytes or the MPE-FEC Reed-Solomon code as specified in [37] any LL-FEC frame ADT sizes up to 191 Kbytes. The chosen code is identified in the forward link signalling.

3.5.3 Return Link

Also for the return link the same considerations about the need to introduce some mitigation techniques in order to accommodate the challenges of mobile environments, can be done. Therefore, some additional mobile functionalities are implemented to adapt the link to the mobile conditions.

3.5.3.1 Spectrum Spreading

In Mobile LOS scenarios, return link carriers can require the use of spectrum spreading in order to reduce the spectral density and in particular off-axis. Indeed, the use of very small antennas necessary to the mobile applications in *Ku* Band is incompatible with the off-axis emissions defined in the ETSI and FCC rules with the existing DVB-RCS waveform.

The spectral spreading can be achieved by two means. The first consists of the use of $\pi/2$-BPSK modulation. This is equivalent to spreading a QPSK modulated signal by a factor 2. The second solution is called *burst repetition* and consists in increasing the symbol rate of the signal by a factor N without increasing the power, as shown in Fig. 3.10. This modification reduces the E_s/N_0 at the receiver side. In order to recover the required E_s/N_0, the signal is repeated N times at the transmitter side.

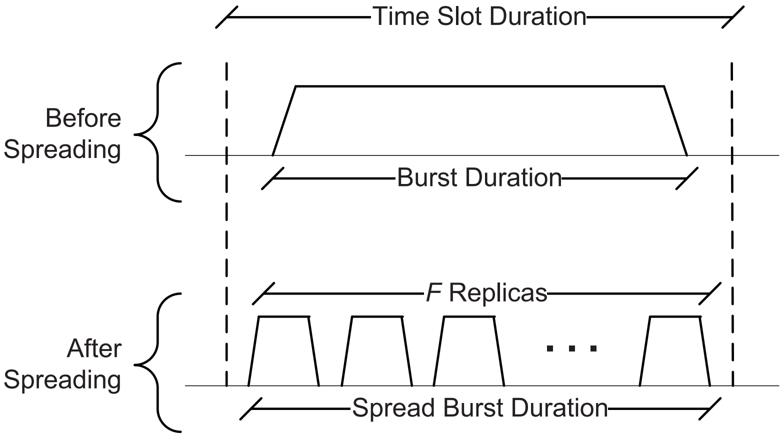

Fig. 3.10 Spectrum spreading in the return link by burst repetition

3.5.3.2 Proactive retransmission techniques

The Proactive Retransmission technique is an outage countermeasure suitable for the return link of a DVB-RCS system operating in mobile NLOS scenarios.

Basically, it consists in the disabling of the RCS transmitter when an outage event is detected. During the fading event, data are buffered in the transmitter and only transmitted when the fading event is over. In this form of the technique, only the physical layer of the terminal is involved. Variants to this mechanism, involving multiple protocol layers, can be foreseen to further improve the system performances.

Proactive retransmission is made possible by the correlation of fading due to signal blockage or shadowing between forward link and return link. As the forward link fading level can be readily estimated by suitable processing of the received DVB-S2 carrier, a threshold on the measured forward link fading can be set to trigger the Proactive Retransmission mechanism. In this regard, the fading level measurement can be done by monitoring the forward link carrier SNIR.

The other condition necessary to enable this technique is that the forward link DVB-S2 signal should be rapidly re-acquired after a short deep fading event. If timing is maintained, frame resynchronization can be carried out within one frame with suitable re-acquisition techniques implemented at the demodulator level.

The main advantage of the Proactive retransmission technique is that it can allow faster retransmission with respect to what is possible if standard TCP recovery mechanisms are relied upon instead. In particular, it is well known that TCP recovery mechanisms can negatively affect the connection throughput and experienced latency particularly if congestion control mechanisms like slow-start or congestion avoidance are triggered, due to the packet losses caused by the link fading instead than true congestion. Proactive retransmission has the capability to minimise such events, in particular when frequent short fading events are foreseen as it typically happens, for example, in the railway scenario due to the effects of the power arches.

3.5.4 Handover in Mobile Satellite Systems

In such a system, different handover scenarios can be identified, as shown in Fig. 3.11, [33]:

1. *Beam* handover
2. *Gateway* handover
3. *Satellite* handover

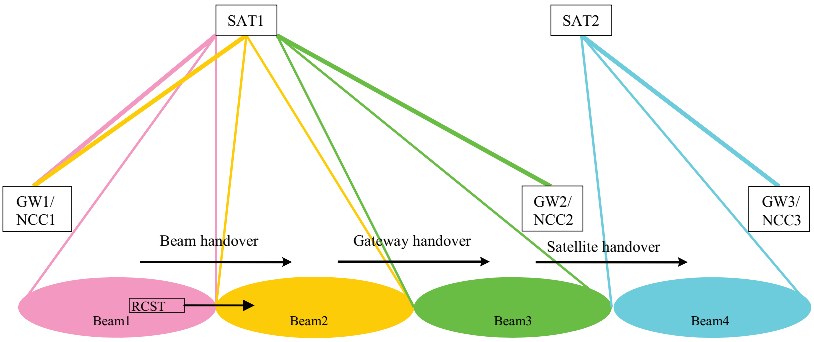

Fig. 3.11 Handover scenarios in mobile satellite systems

Satellite handover always entails beam and gateway handover. Gateway handover always entails beam handover, but can take place within the same satellite delivery network. Thus, the beam handover procedure is tightly integrated and synchronised with the gateway handover.

Beam handover is the preferred technique for mobility management in the case of LOS environment specific to aeronautical applications, but it is also applicable in some cases to maritime applications and even to land applications. A key feature of the beam handover is that the RCST remains attached to the same NCC as it moves from beam to beam through the coverage area. Also the gateway handover considers that the source gateway and the target gateway are associated with the same NCC and with the same satellite.

The handover processes include:

- Handover detection;

- Handover decision;
- Handover execution;
- Resource release/allocation associated with RCST handover;
- Synchronisation of events taking place in RCST and NCC, and associated signalling.

The handover detection determines the need for the mobile RCST to be handed over and typically also determines a list of handover beam candidates. It can take place in RCST or NCC and can be based on position measurements or link quality measurements.

Handover decision is based primarily on the handover recommendation but also on considerations related to the higher layers, in particular with regard to resource management, load balancing and QoS support. It also takes into account the mobility trajectory if it is known, such as the case of a train route or a flight path. It consists of selecting the target beam from the list of beam candidates and issuing the handover command. Once a target beam is chosen, the NCC will check if the chosen target beam belongs to another gateway. If the target beam belongs to a new gateway, a gateway handover is decided. Normally, it is assumed that the forward link and return link have the same beam coverage and gateway configuration so that forward link and return link handovers happen simultaneously.

Handover execution starts with the issuing of the handover command and consists of moving the RCST from a set of resources in the current beam (which are released), to another set of resources allocated in the target beam. Moreover, if also a gateway handover is required, the RCST synchronises with the NCC and the target GW, retunes itself to the new beam and receives traffic from the new beam which comes through the new gateway. In the forward direction, the traffic to the RCST is redirected to the new gateway and then through the new forward link to the moving-in RCST. On the return direction, the RCST sends return traffic and signalling on the new return link and through the new return link to the new gateway.

Further details about handover mechanisms can be found in [33].

3.5.5 Continuous Carrier Mode

DVB-RCS+M introduces the use of a *continuous carrier transmission mode* in the return link in addition to the standard MF-TDMA scheme. This transmission scheme has been adopted as a simple and robust access mechanism for mobile DVB-RCS networks, in particular for RCSTs with substantial traffic aggregation such as those serving trains, cruise ships and aircrafts. Such RCSTs can have a sufficient number of users behind to allow for an efficient use of the continuous carrier mode which has a better physical layer spectral efficiency.

However, it is unlikely that all terminals operate in continuous carrier mode all the time. The system is designed to support a hybrid architecture that retains all the characteristics of a classical MF-TDMA DVB-RCS network, while adding continuous carrier operation as an overlay.

In this new scheme, the forward link is unchanged, except for the addition of some signalling elements needed to control the continuous carrier mode.

The baseline transmission scheme for the continuous return link carriers, instead, is the DVB-S2 system. Return link DVB-S2 carriers can be operated in CCM mode or in ACM mode. A return link continuous transmission can use a very short frame size which is an extension of DVB-S2 standard for mobile environments, [12].

As what concerns, coding and modulation, the coding scheme is based on a concatenation of BCH outer codes and LDPC inner codes like it is in the standard DVB-S2, but the scheme has been modified for use with very short frames while, in addition to the four modulation schemes required by the DVB-S2 (QPSK - 8PSK - 16APSK - 32APSK), a continuous return link carrier can be transmitted also using a $\pi/2 - BPSK$ modulation, as shown in Fig. 3.12. When this is used, it employs absolute encoding (no differential coding). Values from sub-constellations $b1$ and $b2$ are alternately transmitted, starting with the MSB of the Baseband Header of the DVB-S2 (BBHEADER), which is transmitted as $b1$. The normalised average energy per symbol is equal to 1.

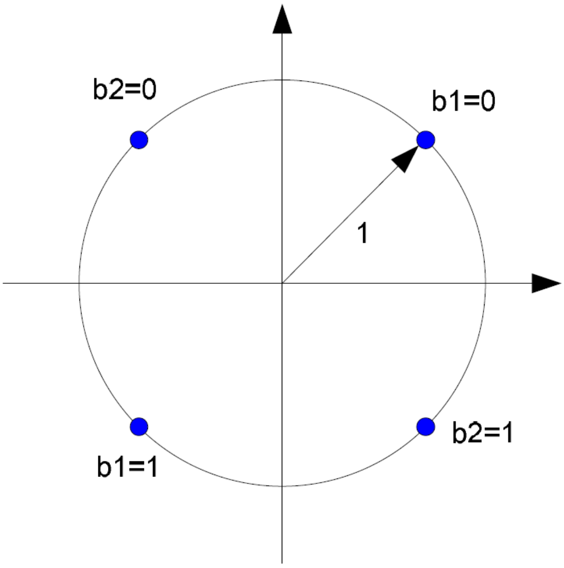

Fig. 3.12 Bit mapping to $\pi/2$-BPSK constellation for continuous return link carrier

Return link continuous carriers can require the use of spectrum spreading for the same

reasons as MF-TDMA transmissions, i.e. to reduce the spectral density, in particular off-axis. The spreading technique to be used is derived from that defined for DVB-S2 forward link transmissions, which is described in subsection 3.5.2.1.
Moreover, the LL-FEC, which has been introduced in 3.5.2.2, can also be applied to the optional continuous return link carrier transmissions, as well.
The comparison between standard MF-TDMA and optional continuous carrier mode shows that, if the continuous carrier mode is adopted, the efficiency can be improved by a factor up to 2.5. But, the real efficiency strongly depends on the traffic load. The carriers is dimensioned with the peak data rate of the mobile terminal but, if the mean data rate (load) is lower than 40% of the full load, the system is less efficient than the classical MF-TDMA one. Concluding, the continuous carrier mode is only well suited to systems with low burstness on the traffic profile. More details about the capacity analysis can be found in [33].

Part II
Cooperative Communications in Satellite Systems

Chapter 4
An Overview on Cooperative Communications

Abstract In this chapter, a general overview on cooperative communications is presented. The adoption of cooperative strategies can be very helpful in those scenarios characterised by continuous occurrence of NLOS and LOS channel conditions and, therefore, it is interesting to assess their implementation also in critical satellite contexts, such as, for example, the mobile satellite one. In fact, cooperative techniques can allow mitigating the deleterious effects of fading thanks to a new form of spatial diversity in which the diversity gain can be achieved through the cooperation of different users which generate a virtual MIMO system.

4.1 Cooperative Approach

Some years ago, a new class of communications, called *cooperative communications*, has been proposed as a valuable alternative to the spatial diversity techniques which require the deployment of additional antennas in order to mitigate the fading effects.

Cooperative communications are based on the concept that a group of mobile terminals can share their single antennas in order to generate a “virtual” multiple antenna, obtaining the same effects than a MIMO system, [39]-[40]. This approach can be seen as a new form of spatial diversity in which, however, the diversity gain can be achieved through the cooperation of different users, opportunely grouped in clusters, which can assume the double role of *active user*, i.e. the user which transmits its own information data and *cooperator*, i.e. the user which “helps” the active user in its transmission, [41]-[42].

The key concept is that each user sees an independent fading process and that spatial diversity can be generated by transmitting each user’s data through different paths, as shown in Fig. 4.1. In fact, an effective way to mitigate the fading effects, is to supply the receiver with multiple replicas of the same information signal transmitted over independent channels. Because of this independence, the probability all considered

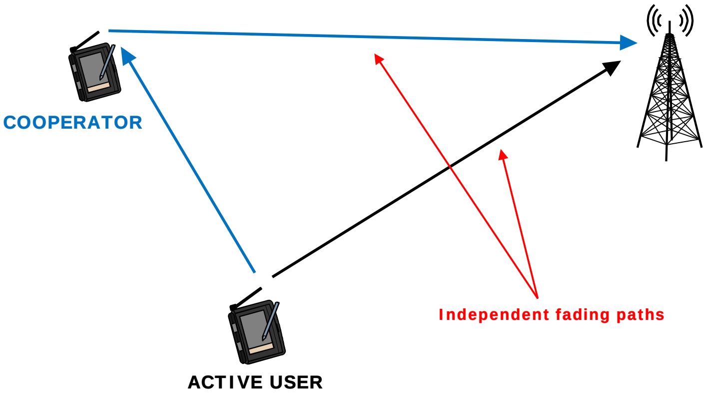

Fig. 4.1 Example of cooperative communications

signals are faded simultaneously, is considerably reduced.
If p, $(0 \leq p \leq 1)$, is the probability that any signal is faded below a threshold value, the probability that all L independent fading channels, containing the same signal, are faded below the threshold value, is given by:

$$p_{tot} = \prod_{i=1}^{L} p = p^L \tag{4.1}$$

and, therefore, it is lower than p, [43].
The cooperative approach turns to be useful for mobile terminals which, because of their size constraints, cannot support multiple antennas and it allows them to increase their performance in terms of Bit Error Rate, Packet Error Rate and Outage probability. The scenarios wherein the idea of cooperation has been applied so far are, mainly, the cellular networks, the wireless sensor networks and the ad hoc networks, but it can be very interesting to consider the adoption of such strategies also in mobile satellite scenarios which are characterised by the continuous occurrence of LOS and NLOS conditions.
There are several cooperative methods which have been proposed in literature ([39]-[40]-[41]-[42]). The main cooperative strategies are:

- *Amplify and Forward* (*AF*)
- *Decode and Forward* (*DF*)
- *Selective Forwarding* (*SF*)
- *Coded-Cooperation*

The *Amplify and Forward* is the simplest cooperative method. In this scheme cooperators receive a noisy version of the signal transmitted by active users which, then, amplify and retransmit towards the final destination. Thus, in this case, also the noise component is amplified and retransmitted by cooperators.

Considering the case of one active user and one cooperator, the amplification factor A can be written as follows, [39]-[44]:

$$A^2 = \frac{P_c}{P_u|h(u,c)|^2 + N} \tag{4.2}$$

being P_c the power of the signal transmitted by the cooperator, P_u the power of the signal transmitted by the active user, $|h(u,c)|^2$ is the coefficient of the channel between active user and cooperator, and N is the noise power.

The *Amplify and Forward* strategy requires minimal processing at cooperator terminals but needs a consistent storage capability of the received signal consuming, therefore, memory resources. This method is particularly efficient when the cooperator is close to final destination, as shown in Fig. 4.2, so that the link from the cooperator to the destination, d_2, is characterized by high signal-to-noise ratios and, hence, the link between the active user and the cooperator, d_1, becomes comparable to the link between the active user and the destination, d_3.

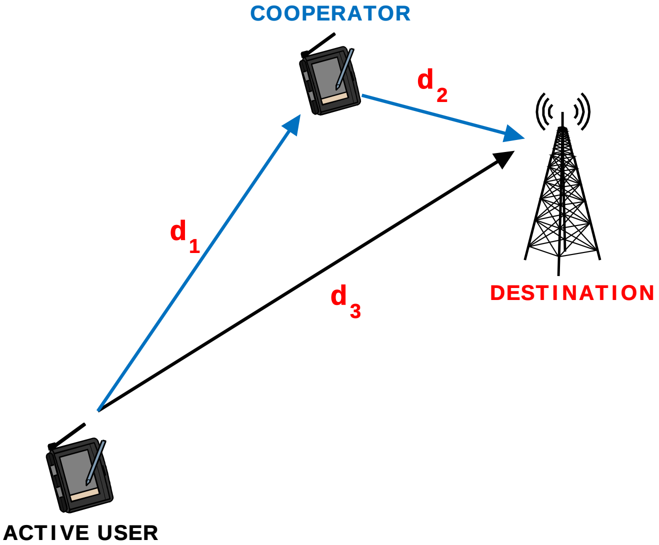

Fig. 4.2 *Amplify and Forward*: efficient terminals displacement

In the traditional *Decode and Forward* scheme, instead, each cooperator always decodes signal coming from the active users, $u(i)$ (with $i = 1 \ldots N_u$ where N_u is total of active users), obtaining an estimate of transmitted signal, $\hat{u}(i)$. Then, it retransmits the signal, $c(i)$:

$$c(i) = \hat{u}(i) \qquad i = 1 \ldots N_u \tag{4.3}$$

after a re-encoding generally with a repetition-coded scheme.

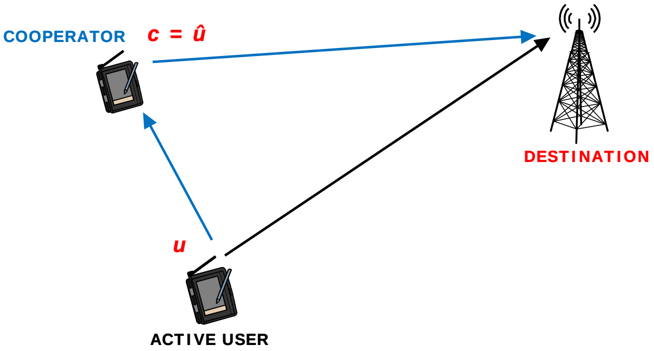

Fig. 4.3 *Decode and Forward* scheme

Although it has the advantage to be a simple scheme, this cooperative method does not achieve diversity. In fact, considering the case of one active user and one cooperator, it is proven that the diversity order is only one, because the overall error probability over two links is dominated by the error probability in the link between the active user and the cooperator, [39]- [45].
Coded-Cooperation and *Selective Forwarding* (*SF*) approaches are the cooperative methodologies considered as reference strategies in this Ph. D. work and are described more in detail in the following.

4.1.1 Coded-Cooperation

In the *Coded-Cooperation*, the cooperative strategy is integrated with channel coding techniques. In this case, instead of producing more replicas of the active user's signal, as it happens in other cooperative methods, the codewords produced by each user belonging to a determined cluster, are divided in different portions which are transmitted through different independent fading channels, by the considered user and by a selected group of users, called *partners*, which are involved in the cooperation process, ([46]-[47]-[48]).
The basic idea is that each user tries to transmit an incremental redundancy of its partners data, besides its own data. Considering, for example, the case of two users, they cooperate by dividing their own codewords of length N, in two successive segments, as shown in Fig. 4.4.
In the first segment, each user transmits a codeword of length N_1 containing its own data, obtained by its original codeword. Then, each user receives and decodes its part-

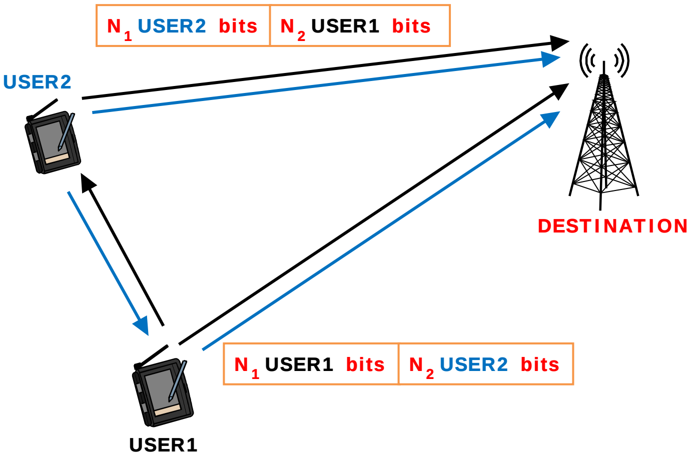

Fig. 4.4 *Coded-Cooperation* scheme

ner's first segment. If this is correctly decoded, each user can compute the additional parity bits of the partner's data and transmit the new codeword of length N_2 containing the partner's data, in the second segment. If the partner's info cannot be correctly decoded, the user reverts to the non-cooperative mode and it transmits its own data. In fact, if a certain terminal is unable to cooperate, because of the wrong reception of the partner's data, it can always use the available capacity to transmit its own data.

The idea of *Coded-Cooperation* is to use the same overall code rate and power for transmission as in a comparable non-cooperative system, i.e. the same system resources are used. Moreover, this cooperation methodology can provide a higher degree of flexibility with respect to other cooperation methods and a higher adaptability to channel conditions, by allowing the use of different channel coding and partitions schemes. For example, the overall code can be a block code or a convolutional code or a combination of both and, then, coded bits to put into the different segments, can be selected through puncturing, product codes, etc., [48].

For these reasons, *Coded-Cooperation* turns to be one of cooperative methodologies more suitable for satellite contexts. According to this, Chapter 5 reports the results of the research activity which has concerned the adoption of *Coded-Cooperation* in a mobile satellite scenario.

4.1.2 Selective Forwarding Cooperation

The *Selective Forwarding* strategy derives from the Decode and Forward technique and it is based on the concept that cooperator users (in the following named simply “cooperators”) repeat active users’ packets by transmitting them through different channel paths with the condition that only the successfully decoded packets received from active users, are sent toward the final destination.

This strategy is more complex than the Decode and Forward method, [39]-[40], because it requires FEC decoding followed by a CRC check to detect possible errors in the packets sent from the active users to the cooperators, but it has some important advantages.

First of all, *Selective Forwarding* is the simplest cooperative method from the perspective of the destination even though it overworks the digital processor at cooperating terminals. Moreover, differently from the Decode and Forward, it allows to achieve diversity and, therefore, to increase the diversity order. Assuming that wireless links between active users and cooperators (d_1), are much better than links between active users and their final destinations, (d_3), as shown in Fig. 4.5, and that all users in the considered cluster see uncorrelated channels, the diversity order can be considered equal to the number of users involved in a transmission (active user and its cooperators), [49]. In this case, *Selective Forwarding* turns to be the best choice for implementing a cooperation process.

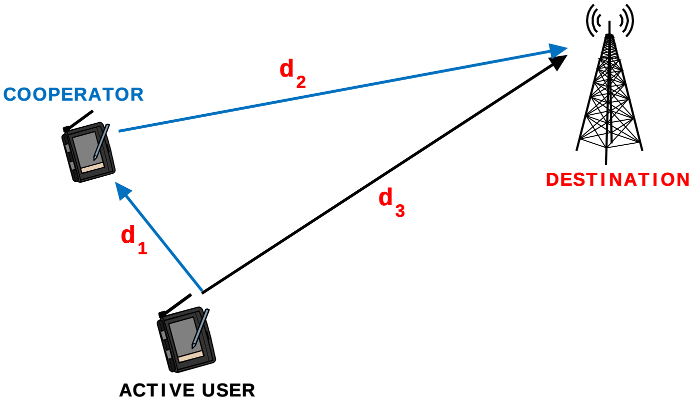

Fig. 4.5 *Selective Forwarding*: best implentation scenario

Since in a return link satellite scenario the previous assumptions can be considered valid, the *Selective Forwarding* scheme can be selected as a right cooperative strategy to be implemented in such kind of environment. For this reason, in Chapter 6 the analysis and the achieved results on the adoption of *Selective Forwarding* cooperation in a critical satellite scenario are presented in detail.

Chapter 5

Adoption of Coded-Cooperation in Mobile Satellite Systems

Abstract This chapter deals with the adoption of *Coded-Cooperation* in a critical satellite scenario. In particular, the performance achieved by DVB-RCS based coded-cooperative terminals in the land-vehicular scenario is reported. *Coded-cooperation* relies on the idea that the bits of each codeword are transmitted in the satellite uplink by different cooperative terminals, thus permitting to achieve virtual long interleaving. The adoption of this strategy can allow improving the performance considerably depending on the used cooperative scheme and the considered number of users which are involved in the cooperation.

5.1 System Model

The considered system model is depicted in Fig. 5.1: a set of N_u vehicular users are interconnected through a reliable (ideal throughout this work) wireless link. The i-th user is characterised by a certain speed, $\mathbf{v_i(t)}$. The users are connected to a terrestrial gateway through a geostationary satellite. The forward link is based on the DVB-S2 standard, [5], while the return link (on which we will focus in the following) is based on DVB-RCS, [7]. Due to the MF-TDMA scheme employed by such standard, as reported in Section 3.1, a certain number of frequency/time slots are assigned to each user within a super-frame depending on the specific demand. How the synchronisation and the cooperation among users are managed in such a context, it is not in the scope of this investigation. We, therefore, base our analysis on the assumption that there is an adequate radio resource management scheme which allows the users to share the uplink effort according to the *Coded-cooperation* scheme. As already mentioned, the proposed type of cooperation does not require additional system resources: the transmit power and the overall information rate in the cooperative system are the same as in a non-cooperative one. Let's assume that the i-th user aims to transmit a message of size k bits. The message is first encoded by the physical layer encoder, obtaining

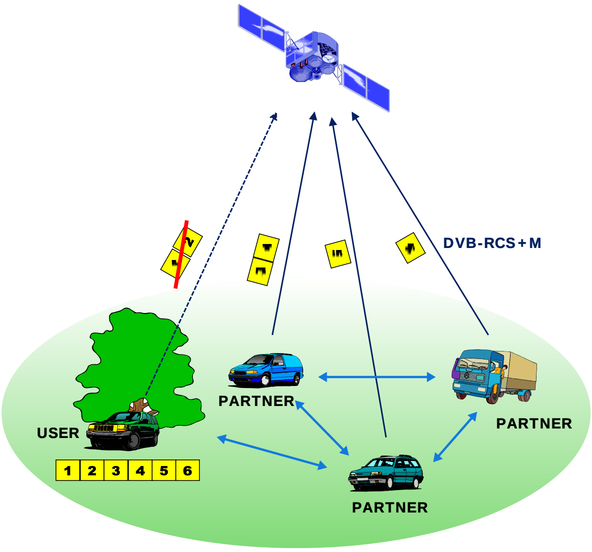

Fig. 5.1 Coded-cooperative scenario

the codeword $\mathbf{c}(\mathbf{i})$ (with $i = 1 \dots N_u$) with size n bits. Once all codewords $\mathbf{c}(\mathbf{i})$ are ready, they are exchanged through terrestrial links among the N_u users. At each user i, each generic message $\mathbf{c}(\mathbf{j})$ coming from the other users, is divided in N_u sub-blocks, $\mathbf{c}(\mathbf{j})$=[$\mathbf{c}_1(\mathbf{j})$, $\mathbf{c}_2(\mathbf{j})$, , $\mathbf{c}_{N_u}(\mathbf{j})$]. A new vector bit $\mathbf{x}(\mathbf{i})$, hereafter referred to as *combined codeword*[1], is then produced by the generic i-th user by combining N_u sub-blocks belonging to different users' codewords. The vector $\mathbf{x}(\mathbf{i})$ will be therefore sent by the i-th user through the satellite link. The selection of the sub-blocks involved in the combined codewords can be based on predefined or random patterns depending on the considered *Coded-cooperation* scheme, under the constraint that all the sub-blocks of a codeword $\mathbf{c}(\mathbf{i})$ are sent through different combined codewords. An example of the procedure with N_u equal to 4, is depicted in Fig. 5.2. At the gateway side, each codeword $\mathbf{c}(\mathbf{i})$ is re-assembled and then input to the physical layer decoder. The above-described procedure can be referred to as a virtual interleaving, where the bits are spread among users (and therefore, in space) rather than in time. This technique permits to achieve long virtual interleaving at the expense of a very low latency. For the purpose of this preliminary evaluation, the latencies introduced by the codeword exchange process through the terrestrial links and by the re-assembling process in the gateway will be ignored.

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[1] Note that a combined codeword does not belong to a specific code book, i.e., it is not a result of an encoding procedure. It represents a concatenation of portions belonging to different actual codewords

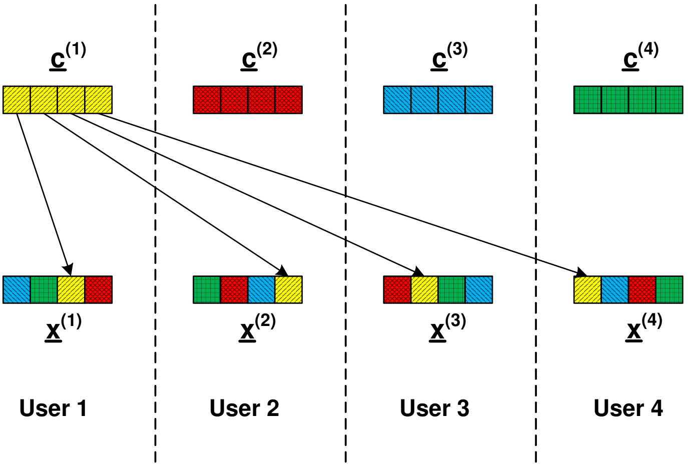

Fig. 5.2 Example of the code combining procedure. $N_u = 4$

5.2 Propagation Channel Model

The adopted propagation channel model for the Land Mobile Satellite (LMS) channel is mainly taken from [34], and it is summarised in this section for the sake of completeness. The model considers a frequency non-selective LMS channel at *Ku* band. In these conditions, a generic passband received signal, $r(t)$, can be written as:

$$r(t) = \mathrm{Re}\{A(t) \cdot \widetilde{s}(t - t_0)e^{j2\pi f_0 t}\} + n(t) \tag{5.1}$$

where $A(t)$ is the multiplicative time-varying channel coefficient, $\widetilde{s}(t)$ the complex-envelope of the transmitted signal, t_0 the propagation delay, f_0 the carrier frequency and $n(t)$ the additive thermal noise.

The channel coefficient is a complex term and, therefore, it can be expressed through its absolute value (also called modulus), $|A(t)|$, and its phase $\phi(t)$:

$$A(t) = |A(t)|e^{\phi(t)} \tag{5.2}$$

The amplitude of the channel coefficient, $|A(t)|$, represents the amplitude of the fading term which, according to this class of models, can be divided into fast and slow fading. Slow fading events, commonly referred to as shadowing, model the attenuation caused by the orography and large obstacles, such as hills, buildings, trees, etc., through absorption and diffraction mechanisms, and they are normally modelled as a finite state machine. Fast fading events, instead, due to the irregularity of the obstacles (e.g. vegetative shadowing) and to the multipath propagation phenomena caused by reflections over surrounding surfaces, can be additionally modelled as superimposed random variations that follow a given Probability Density Function (PDF) for each state.

At an arbitrary time instant t and assuming that the transmitted signal $\widetilde{s}(t)$ has unitary amplitude[2], the overall PDF describing the received signal amplitude, called below $R(t)$, can be written as:

$$p_R(r) = \sum_{k=1}^{N} \Pi_k \cdot p_{R,k}(r) \tag{5.3}$$

being N the number of states, Π_k the absolute probability of being in the state k (that can be easily obtained from the *State Transition Matrix* $S = [p_{ij}]$, containing in each element the probability of transition from the state i to the state j) and $p_{R,k}(r)$ the PDF associated to the fast fading within state k.

Following this approach, a three states (LOS, Shadowed and Blocked) Markov-chain based model is assumed for the fading process, as shown in Fig. 5.3. The *LOS* state is characterised by a Rician PDF of the following form:

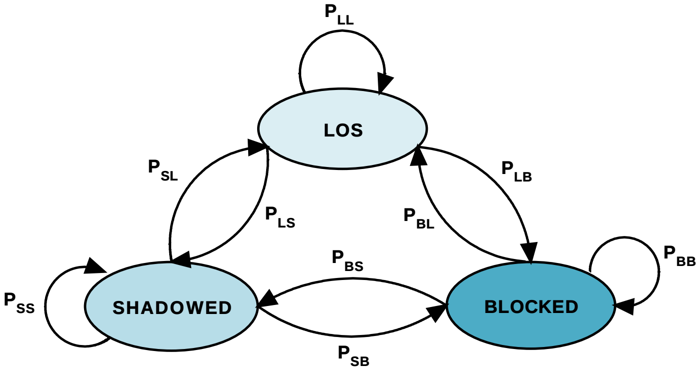

Fig. 5.3 3-states channel model

$$p_R(r) = \frac{r}{\sigma^2} \cdot \exp\left(-\frac{r^2+z^2}{2\sigma^2}\right) \cdot I_0\left(\frac{r \cdot z}{\sigma^2}\right), \qquad r \geq 0 \tag{5.4}$$

being I_0 the zero-order modified Bessel function of the first kind, z the amplitude of the line-of-sight component and σ^2 the power of the real part or the imaginary part of the scattered component.

The *Shadowed* state is characterised by a Suzuki PDF, [50]. The Suzuki process is a product process of a Rayleigh process and a Lognormal (LN) process, [51]-[52]. The slow signal fading is, in this case, modelled by the Lognormal process taking the slow time variation of the average local received power into account. The Rayleigh process

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[2] Under this hypothesis, the received signal amplitude, $R(t)$ corresponds to the amplitude of the fading term, i.e. $R(t) = |A(t)|$.

models, instead, the fast fading. The Suzuki PDF can be expressed as follows, [53]:

$$p_R(r) = \int_0^{+\infty} \left[\frac{r}{\sigma_{ray}^2 L^2} \cdot \exp\left(-\frac{r^2}{2\sigma_{ray}^2 L^2} \right) \right] \cdot \\ \left[\frac{1}{\sqrt{2\pi}\phi\sigma_{ln} L} \cdot \exp\left\{ -\frac{1}{2} \left(\frac{\ln(L) - \phi\mu_{ln}}{\phi\sigma_{ln}} \right)^2 \right\} \right] dL \tag{5.5}$$

wherein the first term represents the conditional joint Lognormal and Rayleigh PDF while the second term is the Lognormal PDF which characterises the random variable L. Moreover, $\phi = \ln 10/20$, and μ_{ln} and σ_{ln} are the mean and standard deviation, respectively, of the associated Gaussian distribution in dB unit.

Finally, the *Blocked* state is characterised by no signal availability. A different set of parameters is provided in Table 5.1 for each of the two environments considered next, namely *highway* and *suburban*. The average state transition period (also called state duration) is equal to 0.0417 s, corresponding to blocks of 1000 samples at the sampling frequency of 24 kHz. The above mentioned state duration refers to average speeds v of 100 Km/h and 40 Km/h for the highway and suburban environments, respectively. Doppler Spectrum is estimated as proposed in [54] and [55], taking into account a realistic antenna beamwidth and the angle between satellite position and terminal direction by means of the following equation:

Environment	*State Transition Matrix*	*π (LOS, SH, BL)*	*Rice z*	*Rice σ*	*Rice Factor*	σ_{ln}	μ_{ln}
Highway	0.9862 0.0138 0.0000	0.8922	0.9892	0.0947	17 dB	1.5 dB	-8 dB
	0.1499 0.8378 0.0123	0.0823					
	0.0008 0.0396 0.9596	0.0255					
Suburban	0.9796 0.0204 0.0000	0.7831	0.9994	0.0829	18 dB	2 dB	-7 dB
	0.0929 0.8571 0.0500	0.1715					
	0.0015 0.1876 0.8109	0.0454					

Table 5.1 *Ku*-band land-vehicular channel parameters

$$S(f) = \begin{cases} \dfrac{A}{f_d\sqrt{1-\left(\dfrac{f}{f_d}\right)^2}} & \text{if} \quad f_d\cos(\phi+\alpha) < f < f_d\cos(\phi-\alpha) \\ 0 & \text{otherwise} \end{cases} \tag{5.6}$$

The following values have been considered:

- $\alpha = \pi/2$
- $f_d = v \cdot f_0/c$
- $2\phi = \theta_{3\ dB} = 70\lambda/D$
- $D = 65$ cm

being D the antenna diameter, v the terminal speed defined above and $f_0 = c/\lambda$, the carrier frequency equal to 14 GHz.

5.3 System Performance

In this section the proposed cooperative system is validated through computer simulations for both considered environments. The set of parameters used in the simulations are those which have been defined in the previous section, in particular in the Table 5.1, as for the channel model parameters, the Doppler Spectrum and the terminal speeds. Moreover, a code rate of $1/3$ and 8 iterations in the turbo decoder have been assumed and ATM traffic bursts size with $N_{atm} = 1$ considered, [7]. Concerning the calculation of the Log-Likelihood Ratios (LLR) values to send to the turbo decoder, the channel state estimation has not been introduced in the simulation model. Performance has been analysed in terms of CER (Codeword Error Rate) vs. E_b/N_0 at the output of the FEC decoder in the gateway.

5.3.1 Highway environment

In the following, some results concerning the highway environment are presented. In the plot in Fig. 5.4, a comparison among three different coded cooperative schemes considering sixteen users, and the non-cooperative case is reported.

In the first two schemes, named *cooperation block* and *cooperation block inter*, the codeword of the i-th user, constituted by a systematic part and a parity part, is divided in as many portions as the number of cooperative users and each of them transmits a combined codeword, as previously explained. The difference between these two schemes is in the rule that assigns each portion of the original codeword to each user. In the first scheme, a simple rule is used: the first user transmits the first portion of the systematic part and the first portion of the parity part of all codewords, the second one transmits the second portion of both parts and so on for all users. In the second scheme, instead, the portions sent by each user are assigned pseudo-randomly bearing however in mind that all sub-blocks of each codeword $\mathbf{c}(\mathbf{i})$ shall be transmitted. So, for instance, the first user transmits the first portion of systematic part but not the first one of the parity part.

In the third scheme, named *cooperation random*, the partitioning of the codeword between systematic part and parity part is not considered anymore. In this case, the codeword portions composing the combined codeword are constituted by the bits of the original codeword of each user, which are assigned to each user using a random rule. Thus, the i-th user can transmit a portion composed by as many systematic bits as parity bits depending on the distribution of the bits that the random rule generated. Using this last scheme the highest randomization level is guaranteed and, as it can be seen in the Fig. 5.4, the deleterious effects of fading can be more effectively counteracted.

Also the performance over the AWGN channel with erasures, in the following named *AWGN+BEC*, is reported. This curve represents a reasonable reference which, for high E_b/N_0 values, could be taken as an acceptable lower bound to the system performance: under the assumption that only the LOS state can be successfully decoded, and in case the diversity introduced by cooperation could break any channel correlation effect, each codeword would in fact virtually face an uncorrelated channel with an erasure rate equal to the NLOS share, given by the sum of P_{SHADOW} and P_{BLOCK} according to Table 5.1. In Fig. 5.5, the cooperation random scheme is further investigated, and it is

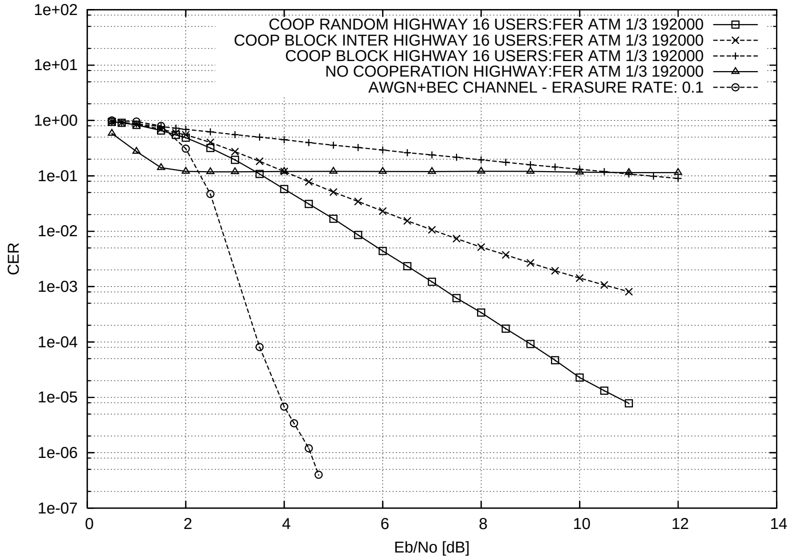


Fig. 5.4 Performance comparison in terms of CER between cooperative (16 users) and non-cooperative schemes for ATM cell, code rate 1/3, data rate 192 kbit/s: HIGHWAY environment

shown how the number of users affects the system performance. It can be seen how, as the number of users increases, the CER values decrease for a fixed E_b/N_0 value. The performance improvement is more remarkable for increasing E_b/N_0 values. Using this scheme it is possible to achieve CER values performing a feasible system which does not present anymore a high floor value as it is, instead, for the non-cooperative case which has a CER floor at 10^{-1}. In particular, it can be noted that the CER value 10^{-5} is achieved for E_b/N_0 equal to 7.7 dB. This results is encouraging also because, if

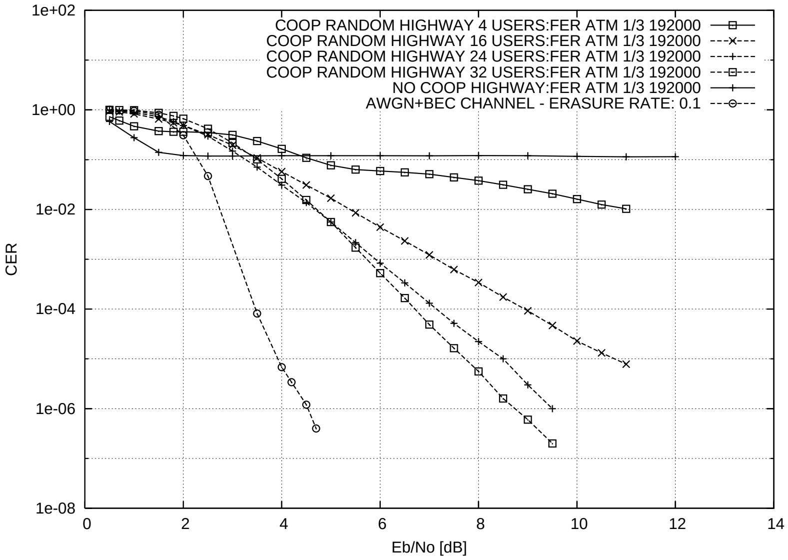


Fig. 5.5 Performance in terms of CER of the cooperation random scheme for different number of users, for ATM cell, code rate 1/3, data rate 192 kbit/s: HIGHWAY environment

the channel state information were introduced in the simulation model, the achieved improving could be more relevant.

5.3.2 Suburban environment

Concerning the suburban scenario, Fig. 5.6 shows the system performance as the number of considered users changes for the cooperation random scheme. It can be seen that, also in this more severe environment, a remarkable improving compared to the non-cooperative scheme can be achieved, mainly at high E_b/N_0 values. Concluding, it is reported in Table 5.2 a comparison between the best achieved E_b/N_0 values in both considered environments and those obtained in the respective *AWGN+BEC* channel. In particular, the gap with respect to the AWGN channel with erasures is shown for two fixed values of CER. It is reasonable supposing that part of this gap could be decreased considering the channel state information which, as already said, has not been implemented in the model.

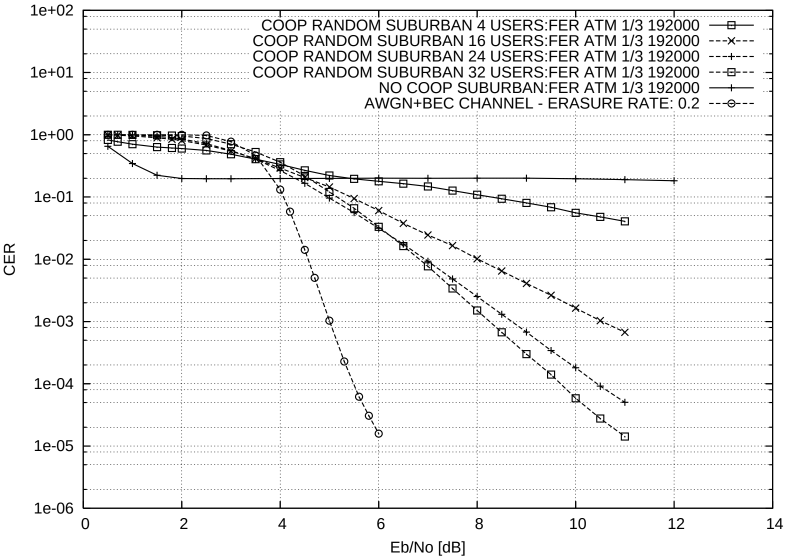


Fig. 5.6 Performance in terms of CER of the *cooperation random* scheme for different number of users, for ATM cell, code rate $1/3$, data rate 192 kbit/s: SUBURBAN environment

	HIGHWAY environment	*Gap wrt AWGN+BEC (erasure = 10%)*	*SUBURBAN environment*	*Gap wrt AWGN+BEC (erasure = 20%)*
CER = 10^{-3}	$E_b/N_0 = 5.7$ dB	2.5 dB	$E_b/N_0 = 8.2$ dB	3.2 dB
CER = 10^{-5}	$E_b/N_0 = 7.7$ dB	3.8 dB	$E_b/N_0 = 11.2$ dB	5 dB

Table 5.2 Comparison between the best simulated scenarios, HIGHWAY and SUBURBAN, and the respective *AWGN+BEC* case with erasure rate equal to NLOS share in terms of E_b/N_0 values and of estimated gap

Chapter 6
Selective Forwarding Cooperation for Critical Satellite Scenarios

Abstract This chapter deals with the adoption of *Selective Forwarding* cooperation techniques in critical satellite scenarios, in particular for DVB-RCS terminals working in a land-vehicular scenario. The adoption of this strategy can enable to improve considerably the system performance depending on the considered number of users which are involved in the cooperation and the different channel conditions which they are subject to. Both the results achieved through several set of computer simulations and the outcomes of a theoretical study on cooperation are presented.

6.1 System Model

In the analysed system model, a set of vehicular DVR-RCS users are interconnected through terrestrial wireless links, as shown in Fig. 6.1. All users are connected to the gateway through a geostationary satellite. The forward link is based on the DVB-S2 standard, [5], while the return link, on which this work is focused, is based on DVB-RCS, [7]. According to the MF-TDMA scheme employed by such a standard, a certain number of frequency/time slots are assigned to users within a superframe depending on their specific demand. Users are divided in *active users* which require to transmit their informative packets and cooperator users (in the following named simply "cooperators") which are, instead, devoted to cooperation.

The analysis considers the adoption, in such a scenario, of a cooperative strategy which allows the users to share the uplink effort according to the *Selective Forwarding* cooperation scheme. Fig. 6.2 shows an example of the used procedure which describes how the resources are allocated and managed in the TDMA scheme. Groups of timeslots, named *frames*, are assigned to active users and cooperators in order that they can transmit their *traffic bursts* (in the following named simply "packets"). Within each superframe, the active users (*User1* and *User2*) convey their informative packets while the cooperators (*Coop A* and *Coop B*) repeat each one half *User1*'s packets and half

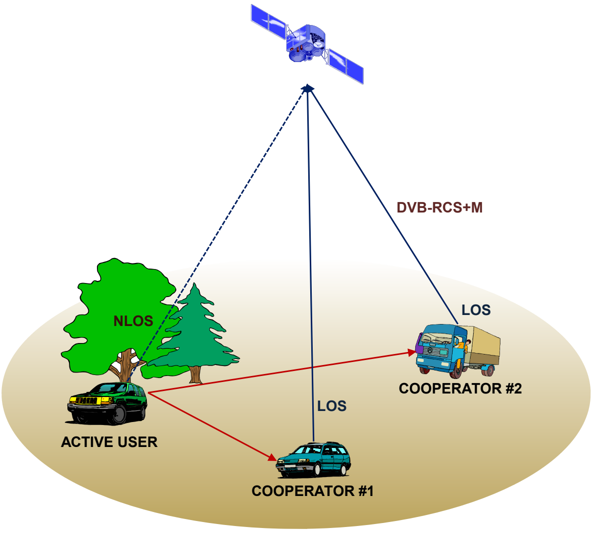


Fig. 6.1 *Selective Forwarding* Cooperative scenario

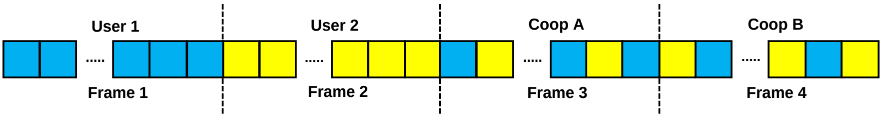
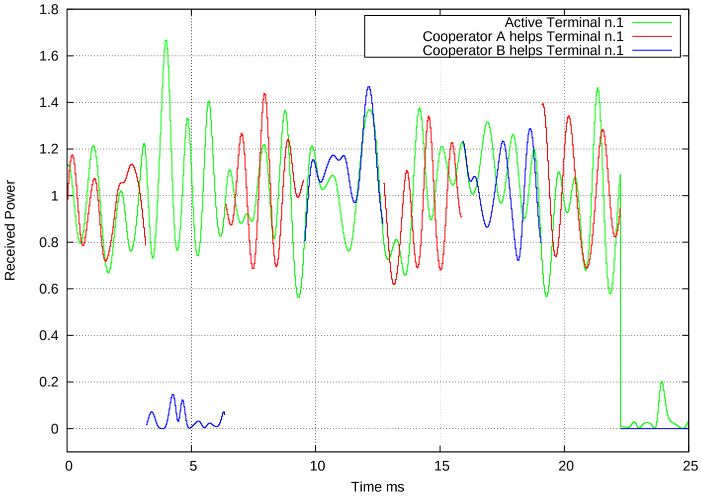


Fig. 6.2 Example of timeslot assignation in a superframe: 2 active users and 2 cooperators

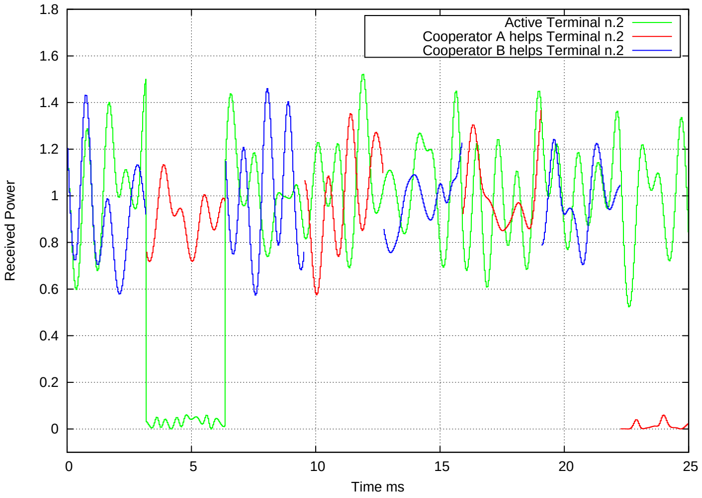
User2's packets in an alternate way. In particular, *Coop A* retransmits before a *User1*'s packet and then a *User2*'s packet, whereas, vice versa, *Coop B* starts repeating before a *User2*'s packet and then a *User1*'s packet. Hence, in this case, two replicas of the same packet for each active user are sent through the satellite and the receiver can apply a CRC mechanism in order to detect the correct packets among those received. Such a method can be simply extended to a different number of active users and cooperators.

The benefits of this procedure can be assessed observing Fig. 6.3 wherein the received signal power of each active user and its cooperators, is reported. In some time portions, in fact, the cooperators can experiment better satellite channel conditions than the active users and their retransmission of packets becomes fundamental in order to not to lose some pieces of information sent by the active users. The receiver can process differently corrupted replicas of the same packet and the probability to detect packets successfully increases considerably.

In the model, the terrestrial wireless links between active users and cooperators, used to share packets, are, initially, characterized by error-free conditions (*ideal case*) because, first of all, it is important to evaluate the efficiency of the cooperative strategy in



(a) *Active user*: *User1*



(b) *Active user*: *User2*

Fig. 6.3 Received signal power of *Active user*, *Cooperator A* and *Cooperator B*

the satellite land-vehicular scenario. Afterwards, it has been considered the case where the terrestrial links are affected by a determined error probability, function of the path loss term calculated for each active user-cooperator link (*real case*). The cooperative method works in the same way than in the *ideal case*, i.e. the packets are retransmitted by cooperators through the satellite link even if they are affected by errors. This is a simplification in the implementation of the *Selective Forwarding* scheme which, instead, requires that each cooperator decodes the packets received from the active users and sends only the successfully decoded packets. However, being the considered terrestrial wireless links between active users and cooperators better than satellite links, the diversity is equally achieved. Fig. 6.4 shows the three considered real scenarios while Table 6.1 reports the terrestrial parameters expressed in terms of Bit Error Rate (BER) which characterises the considered terrestrial link and relative distances between active users and cooperators. In the Table, it is reported the case of 4 cooperators: 2 cooperators are of type *A*, *Coops A*, (*A1* and *A2*) and 2 cooperators of type *B*, *Coops B*, (*B1* and *B2*) and they work as described above. The BER values have been calculated using the equations modelling the terrestrial channel reported in Section 6.2.2. The system performance improvements, resulting from the adoption of this cooperation strategy, depend on the number of users which can be involved in the cooperation and the different channel conditions which they are subject to. Therefore, in order to show the effectiveness of the proposed solution, in Section 6.3, the results describing the system performance are presented in details, considering both the *ideal* case and the *real* one.

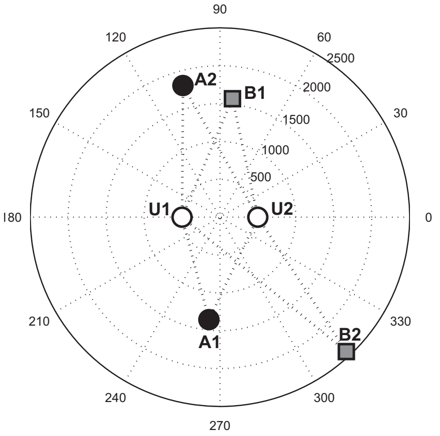
		***Real* case 1**		***Real* case 2**		***Real* case 3**	
		BER	*Distance*	*BER*	*Distance*	*BER*	*Distance*
*CoopA*1	*User*1	10^{-9}	1400 m	10^{-8}	1500 m	10^{-8}	1500 m
	*User*2	10^{-8}	1500 m	10^{-7}	1600 m	10^{-7}	1600 m
*CoopB*1	*User*1	10^{-6}	1700 m	10^{-7}	1600 m	10^{-2}	2800 m
	*User*2	10^{-7}	1600 m	10^{-8}	1500 m	10^{-3}	2300 m
*CoopA*2	*User*1	10^{-5}	1900 m	10^{-2}	2800 m	10^{-7}	1600 m
	*User*2	10^{-4}	2000 m	10^{-3}	2300 m	10^{-8}	1500 m
*CoopB*2	*User*1	10^{-2}	2800 m	10^{-2}	2800 m	10^{-2}	2800 m
	*User*2	10^{-3}	2300 m	10^{-2}	2800 m	10^{-2}	2800 m

Table 6.1 Terrestrial *real cases* parameters

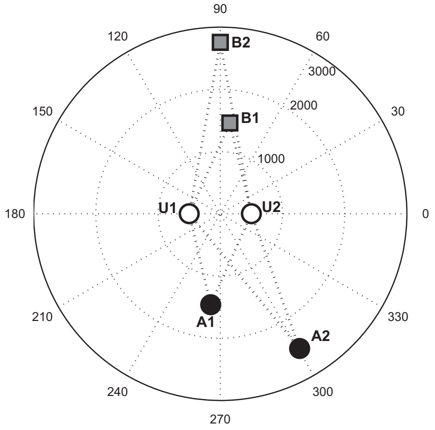
6.2 Propagation Channel Models

6.2.1 Satellite Channel Model

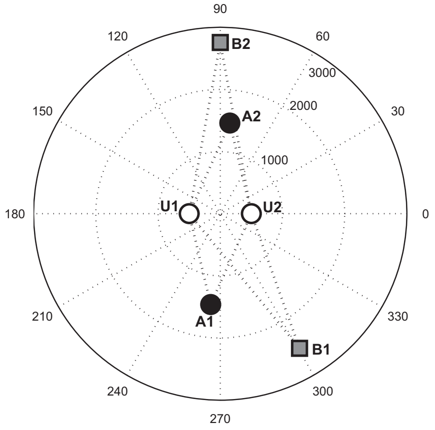
The adopted propagation channel model for the Land Mobile Satellite channel is the same considered in the previous chapter in Section 5.2 and it is summarised in this section for the sake of clarity. As already said, this model considers a frequency non-selective LMS channel at *Ku* band wherein a three states (LOS, Shadowed and



(a) *Real* case 1



(b) *Real* case 2



(c) *Real* case 3

Fig. 6.4 Users and cooperators displacements

Blocked) Markov-chain based model is proposed for the fading process. According to this class of models, the amplitude of the channel coefficient, which represents the amplitude of the fading term, is divided into fast and slow fading. Slow fading events are normally modelled as a finite state machine while, fast fading events, due to the irregularity of the obstacles and to the multipath propagation phenomena caused by reflections over surrounding surfaces, can be additionally modelled as superimposed random variations that follow a given PDF for each state. Considering an arbitrary time instant t and assuming that the transmitted signal has unitary amplitude[1], the overall PDF describing the received signal amplitude, called below $R(t)$, can be written as:

$$p_R(r) = \sum_{k=1}^{N} \Pi_k \cdot p_{R,k}(r) \tag{6.1}$$

being N the number of states, Π_k the absolute probability of being in the state k (that can be easily obtained from the *State Transition Matrix* $S = [p_{ij}]$, containing in each element the probability of transition from the state i to the state j) and $p_{R,k}(r)$ the PDF associated to the fast fading within state k.

The *LOS* state is characterised by a Rician PDF of the following form:

$$p_R(r) = \frac{r}{\sigma^2} \cdot \exp\left(-\frac{r^2+z^2}{2\sigma^2}\right) \cdot I_0\left(\frac{r \cdot z}{\sigma^2}\right), \qquad r \geq 0 \tag{6.2}$$

being I_0 the zero-order modified Bessel function of the first kind, z the amplitude of the line-of-sight component and σ^2 the power of the real part or the imaginary part of the scattered component.

The *Shadowed* state is characterised by a Suzuki PDF, [50]. The Suzuki process is a product process of a Rayleigh process and a Lognormal (LN) process, [51]-[52]. The slow signal fading is, in this case, modelled by the Lognormal process taking the slow time variation of the average local received power into account. The Rayleigh process models, instead, the fast fading. The Suzuki PDF can be expressed as follows, [53]:

$$\begin{aligned} p_R(r) = \int_0^{+\infty} & \left[\frac{r}{\sigma_{ray}^2 L^2} \cdot \exp\left(-\frac{r^2}{2\sigma_{ray}^2 L^2}\right)\right] \cdot \\ & \left[\frac{1}{\sqrt{2\pi}\phi\sigma_{ln} L} \cdot \exp\left\{-\frac{1}{2}\left(\frac{\ln(L)-\phi\mu_{ln}}{\phi\sigma_{ln}}\right)^2\right\}\right] dL \end{aligned} \tag{6.3}$$

wherein the first term represents the conditional joint Lognormal and Rayleigh PDF while the second term is the Lognormal PDF which characterises the random variable L. Moreover, $\phi = \ln 10/20$, and μ_{ln} and σ_{ln} are the mean and standard deviation, respectively, of the associated Gaussian distribution in dB unit.

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[1] Under this hypothesis, the received signal amplitude, $R(t)$, corresponds to the amplitude of the fading term, $|A(t)|$, i.e. $R(t) = |A(t)|$.

Finally, the *Blocked* state is characterised by no signal availability. A different set of parameters is provided in Table 6.2 for each of the two environments considered next, namely *highway* and *suburban*. The average state transition period (also called state duration) is equal to 0.0417 s, corresponding to blocks of 1000 samples at the sampling frequency of 24 kHz. The above mentioned state duration refers to average speeds v of 100 Km/h and 40 Km/h for the highway and suburban environments, respectively. Doppler Spectrum is estimated as proposed in [54] and [55], taking into account a realistic antenna beamwidth and the angle between satellite position and terminal direction by means of the following equation:

Environment	*State Transition Matrix*	π *(LOS, SH, BL)*	*Rice* z	*Rice* σ	*Rice Factor*	σ_{ln}	μ_{ln}
Highway	0.9862 0.0138 0.0000 0.1499 0.8378 0.0123 0.0008 0.0396 0.9596	0.8922 0.0823 0.0255	0.9892	0.0947	17 dB	1.5 dB	-8 dB
Suburban	0.9796 0.0204 0.0000 0.0929 0.8571 0.0500 0.0015 0.1876 0.8109	0.7831 0.1715 0.0454	0.9994	0.0829	18 dB	2 dB	-7 dB

Table 6.2 Land-vehicular satellite channel parameters

$$S(f) = \begin{cases} \dfrac{A}{f_d\sqrt{1-\left(\dfrac{f}{f_d}\right)^2}} & \text{if} \quad f_d\cos(\phi+\alpha) < f < f_d\cos(\phi-\alpha) \\ 0 & \text{otherwise} \end{cases} \tag{6.4}$$

The following values have been considered:

- $\alpha = \pi/2$
- $f_d = v \cdot f_0/c$
- $2\phi = \theta_{3\ dB} = 70\lambda/D$
- $D = 65$ cm

being D the antenna diameter, v the terminal speed defined above and $f_0 = c/\lambda$, the carrier frequency equal to 14 GHz.

6.2.2 Terrestrial Channel Model

The considered terrestrial channel model is a simple model wherein each terrestrial link is affected by a determined error probability, function of the path loss. No multipath fading is considered in this investigation. The path loss term is due to the distance between active users and cooperators, calculated at the middle-band frequency and it is modelled by:

$$L_{|d} = \left(\frac{4\pi d}{\lambda}\right)^{\alpha} \tag{6.5}$$

wherein the exponent α models the attenuation dependence from the distance, $\lambda = c/f$ is the central frequency wave length and d is the distance between each pair active user-cooperator. In the analysed case, α is equal to 3 considering a medium density urban scenario while f is equal to 2.4 GHz. The error probability at the distance d, in case of AWGN (Additive White Gaussian Noise) channel conditions and QPSK modulation scheme, can be expressed through the following equation:

$$P_e\left(\frac{E_b}{N_0}\right)_d = \frac{1}{2}\ \mathrm{erfc}\ \sqrt{\frac{(E_b/N_0)_{|2Km} \cdot L_{|2Km}}{L_{|d}}} \tag{6.6}$$

where the term $(E_b/N_0)_{|2Km}$ is estimated assuming a BER value equal to 10^{-4} at a distance of $2Km$ between active user and cooperator.

6.3 System Performance

In this section the proposed cooperative system is validated through computer simulations analysing the considered cases (*ideal* and *real*) and environments (*highway* and *suburban*). The set of parameters used in the simulations are those which have been defined in Table 6.1 as for the terrestrial Real cases parameters, and in the previous section, in particular in Table 6.2, as what concerns the satellite channel model parameters, the Doppler Spectrum and the terminal speeds. Moreover, a code rate of $1/3$ and 8 iterations in the turbo decoder have been assumed and the ATM traffic burst size with $N_{atm} = 1$ considered, [7]. Concerning the calculation of the Log-Likelihood Ratios (LLR) values to send to the turbo decoder, the channel state estimation has not been introduced in the simulation model. Performance has been analysed in terms of BER and PER[2] vs. E_b/N_0 at the output of the FEC decoder in the gateway.

6.3.1 Ideal case

In the following, some results concerning the ideal case are presented. First of all, it is shown how the number of involved cooperators affects the system performance. In particular, in Fig. 6.5 and in Fig. 6.6, the performance comparison in terms of average PER and of average BER, respectively, between the no cooperation and cooperation

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[2] As said in Section 6.1, a “packet” is a traffic burst, in particular an ATM traffic burst of size 53 Bytes.

(with 2 cooperators and 4 cooperators) cases in the HIGHWAY environment is reported. Fig. 6.7 and Fig. 6.8 show the same performance comparison but considering the SUBURBAN environment. The number of active users is considered equal to 2 in all simulated cases. Focusing mainly on the Figure 6.5, it can be seen that as the number of cooperators increases, the PER values decrease considerably for fixed E_b/N_0 values and, in particular, it can be noted that, the case considering 4 cooperators has a PER floor at about $2 \cdot 10^{-3}$ for E_b/N_0 values starting from 2 dB with respect to the no cooperation case which has, instead, a PER floor at $1.1 \cdot 10^{-1}$. The presence of PER floors is due to the occurrence, with the given probabilities already shown in Table 6.2, of Shadowed and Blocked state channel conditions. However, the context taken into account for satellite broadband communications is, mainly, that of elastic IP traffic generated by applications like e-mail, web browsing, FTP and TELNET services, which are not completely compromised by a delay, loss, or bandwidth limitations, due also to the occurrence of NLOS channel conditions. For these reasons, it is worth analysing how the cooperation strategy affects the system performance when LMS channel is only in LOS or in NLOS conditions in order to evaluate the realistic behaviour of the system which works for the most part of the time in LOS conditions. The LOS state is, as a matter of facts, the state with the highest absolute probability (89.22% in the highway environment and 78.31% in the suburban environment).

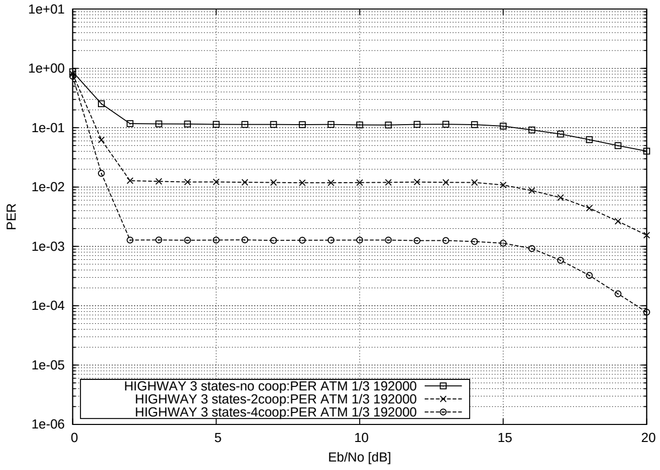

Fig. 6.5 PER performance for ATM cell, code rate 1/3, data rate 192 kbit/s, HIGHWAY environment: 3 states - *Ideal* case 4 cooperators, 2 cooperators and no cooperation cases

Fig. 6.9 shows, therefore, the comparison in terms of PER between no cooperation and cooperation (4 cooperators) cases considering the satellite channel being only in the LOS state or only in the Shadowed state. The Blocked state, as already said, is characterised by no signal availability so the achieved BER values are equal to 0.5. The

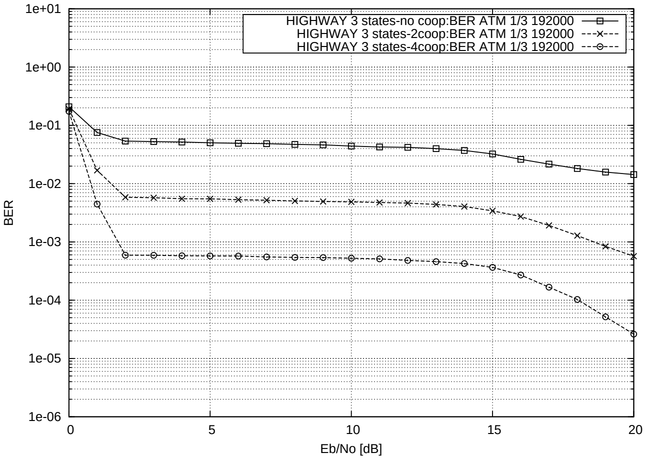

Fig. 6.6 BER performance for ATM cell, code rate 1/3, data rate 192 kbit/s, HIGHWAY environment: 3 states - *Ideal* case 4 cooperators, 2 cooperators and no cooperation cases

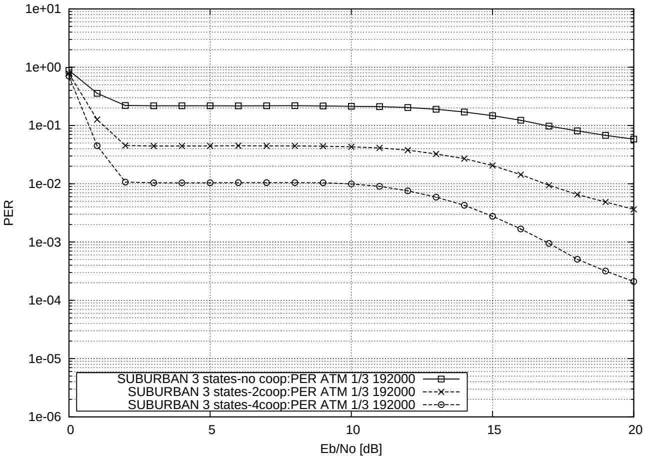

Fig. 6.7 PER performance for ATM cell, code rate 1/3, data rate 192 kbit/s, SUBURBAN environment: 3 states - *Ideal* case 4 cooperators, 2 cooperators and no cooperation cases

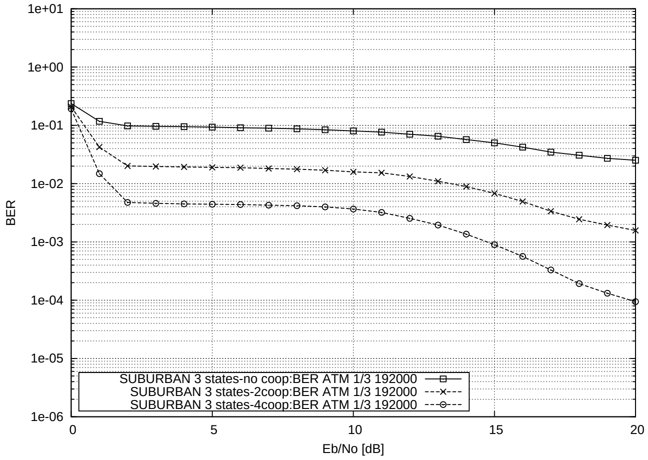

Fig. 6.8 BER performance for ATM cell, code rate 1/3, data rate 192 kbit/s, SUBURBAN environment: 3 states - *Ideal* case 4 cooperators, 2 cooperators and no cooperation cases

results concerning the LOS state are encouraging because they show that the adoption of the cooperation (4 cooperators) allows to improve the system performance achieving the PER value 10^{-6} with a gain equal to 1.4 dB with respect to the case of absence of cooperation.

6.3.2 Real case

After assuming the terrestrial wireless link connecting users as ideal, it has been carried out a set of simulation performing the real case introduced in the previous sections. Fig. 6.10 and Fig. 6.11 show the system performance in terms of average PER considering the satellite channel characterised both by the 3 states and only by the LOS state, respectively. The curve obtained in ideal conditions can be considered as a lower bound to the system performance. In both graphs, it can be seen that the *Real* case 1 achieves the best performance while the *Real* case 3 the worst one. This happens because the *Real* case 1 has the 4 cooperators, both *Coops A* (*A1* and *A2*) and *Coops B* (*B1* and *B2*), displaced in increasing order in terms of distance active user-cooperator and error probability values while, in the *Real* case 3, both *Coops A* (*A1* and *A2*) are closer to the active users and, therefore, encounter links characterised by lower error probability, than both *Coops B* (*B1* and *B2*). This means that the first

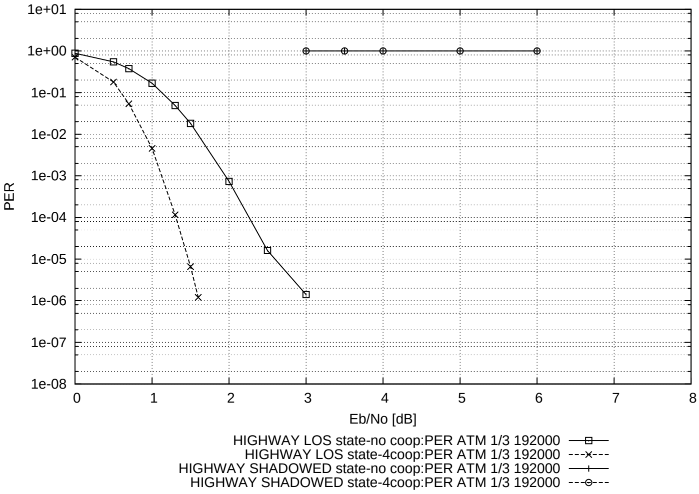

Fig. 6.9 PER performance for ATM cell, code rate $1/3$, data rate 192 kbit/s, HIGHWAY environment: LOS state and Shadowed state - *Ideal* case 4 cooperators and no cooperation cases

half of packets is received and retransmitted successfully by the *Coops A* while the second half is transmitted on the satellite link more deteriorated by *Coops B* because they encounter worse terrestrial channel conditions. Considering the results achieved

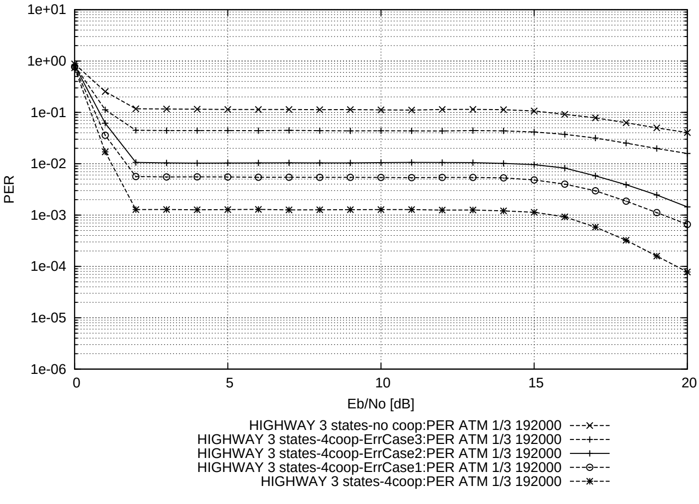

Fig. 6.10 PER performance for ATM cell, code rate $1/3$, data rate 192 kbit/s, HIGHWAY environment: 3 states - *Ideal* case 4 cooperators, 3 *Real* cases 4 cooperators and no cooperation case

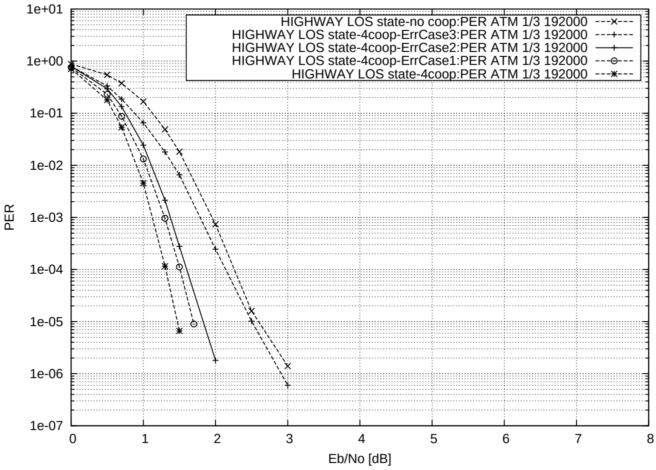

Fig. 6.11 PER performance for ATM cell, code rate $1/3$, data rate 192 kbit/s, HIGHWAY environment: LOS state - *Ideal* case 4 cooperators, 3 *Real* cases 4 cooperators and no cooperation case

in the suburban environment, these ones confirm what said for the highway scenario. Fig. 6.12 and Fig. 6.13 show the system performance in terms of average BER considering, also in this case, the satellite channel characterised both by 3 states (Fig. 6.12) and only by the LOS state (Fig. 6.13). It can be seen that, also in this more severe

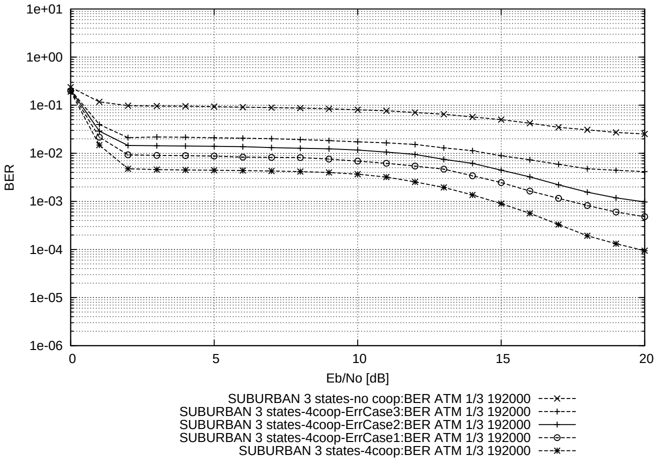

Fig. 6.12 BER performance for ATM cell, code rate $1/3$, data rate 192 kbit/s, SUBURBAN environment: 3 states - *Ideal* case 4 cooperators, 3 *Real* cases 4 cooperators and no cooperation case

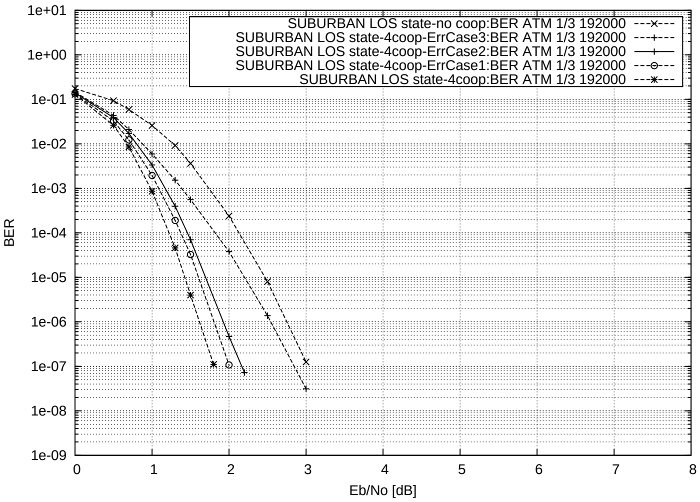

Fig. 6.13 BER performance for ATM cell, code rate $1/3$, data rate 192 kbit/s, SUBURBAN environment: LOS state - *Ideal* case 4 cooperators, 3 *Real* cases 4 cooperators and no cooperation case

environment, a remarkable improving compared to the no cooperation case can be achieved, mainly observing the curves reporting the simulations carried out considering the satellite channel being in the LOS state. In this latter case, the cooperation gain with respect to the no cooperation case, is equal to 1 dB if the best real case (*Real* case 1) is considered while it achieves 1.2 dB compared to the ideal cooperation case.

6.4 Theoretical Analysis on Cooperation

In order to deepen the study of the cooperation techniques in severe satellite scenarios and to validate the results achieved through computer simulations shown above in this chapter, a theoretical analysis on cooperation has been performed, as well. The study aims at showing how the cooperation modifies the statistics of the fast fading in each state of the land mobile satellite channel. In particular, it is proven that the cooperation statistically increases amplitudes values, compared with the no cooperation case, of the random variable which represents the overall fast fading in case of cooperation, moving the Probability Density Function (PDF) and the Cumulative Density Function (CDF) curves towards bigger values in the x-axis, as it is shown in the graphs in the following.

The analysis considers the case of two users, one *active* and one *cooperator*, which adopt the selective forwarding scheme and wherein the terrestrial wireless link between them, used to share packets, is characterised by error-free conditions and, therefore, it is not taken into account in the analysis. Moreover, an *ideal cooperation* is considered, in the sense that the random variable z which characterises the cooperation case, is assumed to be given by the maximum between the two random variables, x and y, which describe the fast fading faced by the active user and the cooperator, respectively:

$$z = max(x,y) \tag{6.7}$$

The Cumulative Density Function of the variable z is given by:

$$CDF_Z(z) = Pr\{Z \leq z\} = \int_{-\infty}^{z} p_Z(t)\,\mathrm{d}t \tag{6.8}$$

For the calculation of the $CDF_Z(z)$, with z given by the expression in (6.7), both the case wherein $x < y$ and the case wherein $y < x$ have to be taken into account. Hence, the $CDF_Z(z)$ can be expressed in the following way:

$$CDF_Z(z) = \int_{-\infty}^{z}\int_{-\infty}^{x} p_{X,Y}(x,y)\,\mathrm{d}x\,\mathrm{d}y + \int_{-\infty}^{z}\int_{-\infty}^{y} p_{X,Y}(x,y)\,\mathrm{d}y\,\mathrm{d}x \tag{6.9}$$

being $p_{X,Y}(x,y)$ the joint probability density function of the random variables x and y. Then, assuming the random variables x and y independent from each other, the joint probability density function can be expressed with the product of the probability density functions of each single variable and the $CDF_Z(z)$ becomes the following:

$$CDF_Z(z) = \int_{-\infty}^{z} \mathrm{d}x \int_{-\infty}^{x} \mathrm{d}y\; p_X(x) p_Y(y) + \int_{-\infty}^{z} \mathrm{d}y \int_{-\infty}^{y} \mathrm{d}x\; p_X(x) p_Y(y) \tag{6.10}$$

wherin $p_X(x)$ and $p_Y(y)$ are the probability density functions of the random variables x and y, respectively.

The Probability Density Function of the variable z, $p_Z(z)$, can be derived from the CDF expression, as follows:

$$p_Z(z) = \frac{\mathrm{d}}{\mathrm{d}z} CDF_Z(z) \tag{6.11}$$

Focusing on the considered propagation satellite channel model, described in detail in Section 5.2, each of three considered states (*LOS*, *Shadowed* and *Blocked*) is characterised by a different PDF. Summarising, the LOS state is characterised by a Ricean PDF, the Shadowed state by a Suzuki PDF and the Blocked state by no signal availability.

The analysis has been carried out making a comparison between the CDF and PDF curves concerning the no cooperation case and the cooperation case. The parameters used in the calculation of statistical functions are those reported in Table 5.1 for the highway environment.

Starting from the best case, wherein both the active user and the cooperator see a channel in LOS state, Fig. 6.14 and Fig. 6.15 show that the cooperation statistically increases amplitudes values of the random variable which represents the fast fading in the cooperative scenario. This means that, in presence of cooperation, transmitted packets face an equivalent channel characterised by better conditions, i.e. the multiplicative channel coefficient $A(t)$ is, on average, higher than in the no cooperation scenario. Therefore, the quality of the received signal is improved and the error probability at receiver decreases, as shown also in the graphs obtained through the computer simulations. The same results can be achieved also considering the case wherein the cooperator sees a channel in Shadowed state whereas the case wherein the satellite channel faced by the cooperator is in the Blocked state, is not so relevant because the Blocked state is characterised by no signal availability and the CDF in case of cooperation, $CDF_Z(z)$, is reduced to:

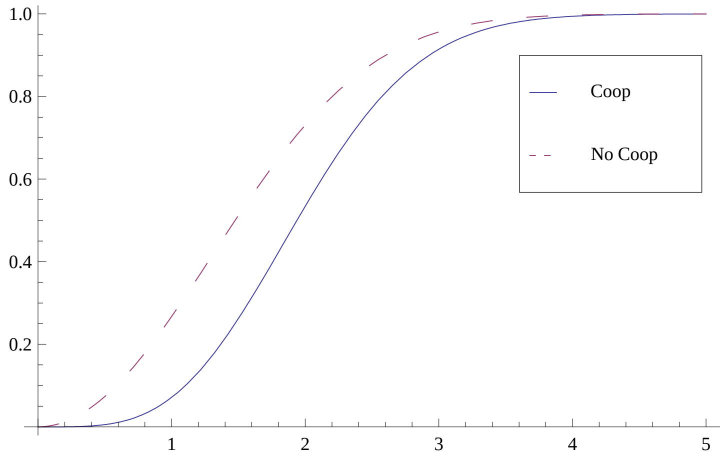

Fig. 6.14 *Active user and Cooperator in LOS state*: Rice CDF (no cooperation case) and Rice-Rice CDF (cooperation case)

$$CDF_Z(z) = \int_{-\infty}^{z} p_X(x)\,\mathrm{d}x \tag{6.12}$$

where $p_X(x)$ is the probability density function of the variable which characterises the fast fading seen by the active user. Therefore, in this case, the $CDF_Z(z)$ is equal to $CDF_X(x)$ which is given by:

$$CDF_X(x) = \int_{-\infty}^{x} p_X(t)\,\mathrm{d}t \tag{6.13}$$

i.e. there is no difference between the cooperation and no cooperation cases.

Concerning the case where both the active user and the cooperator see a channel in

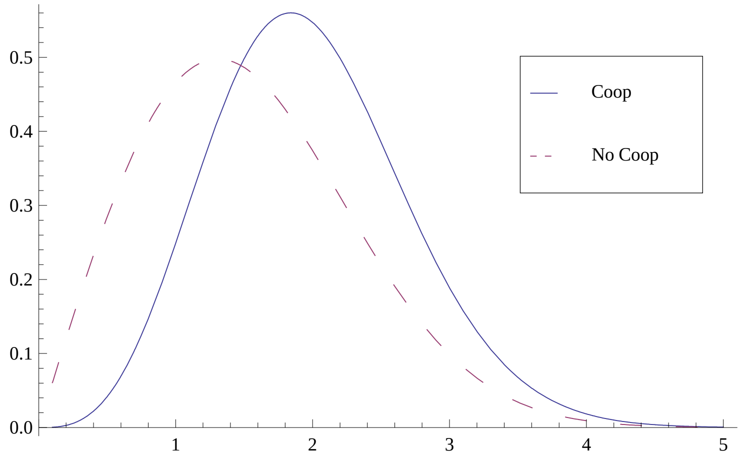

Fig. 6.15 *Active user and Cooperator in LOS state*: Rice PDF (no cooperation case) and Rice-Rice PDF (cooperation case)

Shadowed state, some considerations about the distributions involved can be done. The Suzuki distribution, whose PDF is reported in Fig. 6.16, is given by the product of a Rayleigh process and a Lognormal process whose PDF is reported Fig. 6.17. The

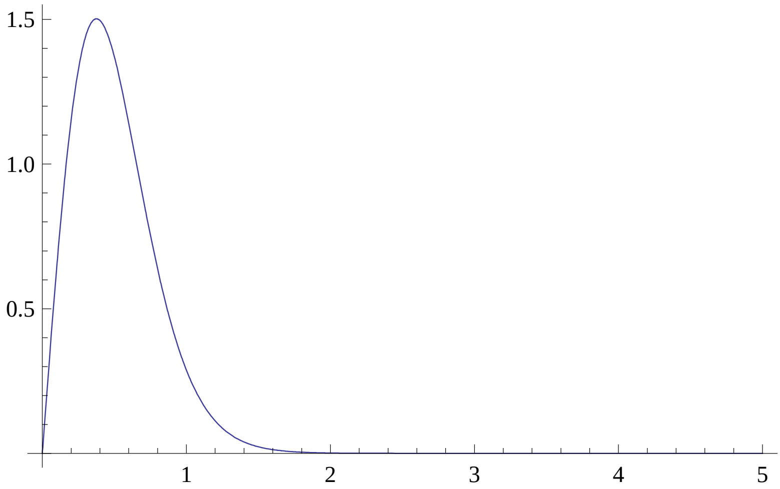

Fig. 6.16 *Active user in Shadowed state*: Suzuki PDF

Lognormal term, because of its small standard deviation value (see Table 5.1), heavily influences the final distribution, making the range of the compound variable more narrow. Comparing the cooperation and the no cooperation cases for the Rayleigh and

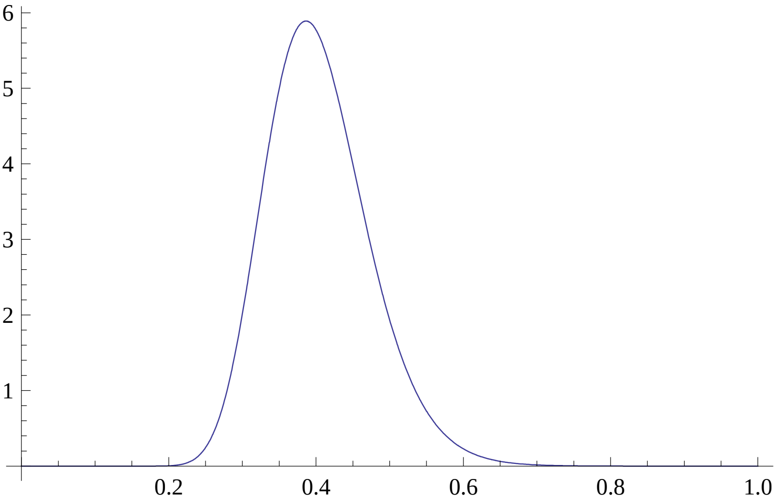

Fig. 6.17 Lognormal probability density function

the Lognormal components, separately, as reported in Fig. 6.18, Fig. 6.19, Fig. 6.20 and Fig. 6.21, it can be noted that, although considering only the Rayleigh component the cooperation takes some advantages, on the Lognormal term, it has less effects and, therefore, the whole benefit is less significant. Hence, it can be stated that, in the case

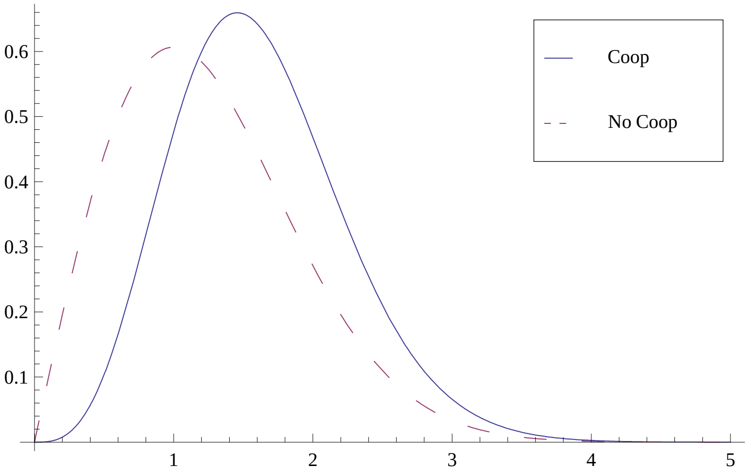

Fig. 6.18 *Active user and Cooperator in Shadowed state*: Rayleigh PDF (no cooperation case) and Rayleigh-Rayleigh PDF (cooperation case)

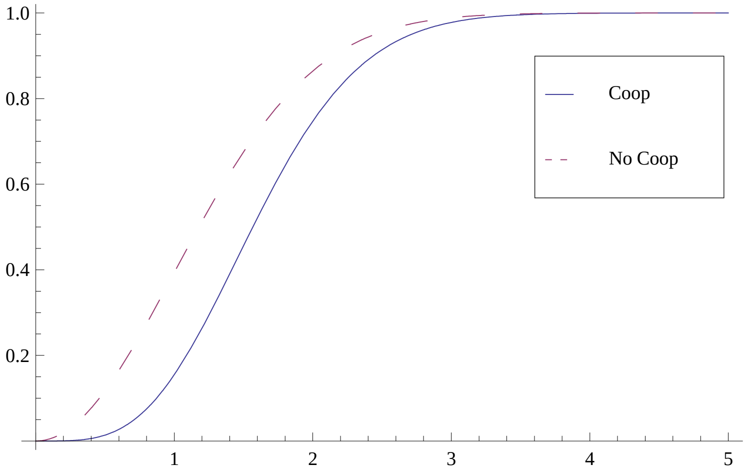

Fig. 6.19 *Active user and Cooperator in Shadowed state*: Rayleigh CDF (no cooperation case) and Rayleigh-Rayleigh CDF (cooperation case)

wherein the cooperator faces the channel in Shadowed state, the use of cooperation does not improve considerably the system performance.

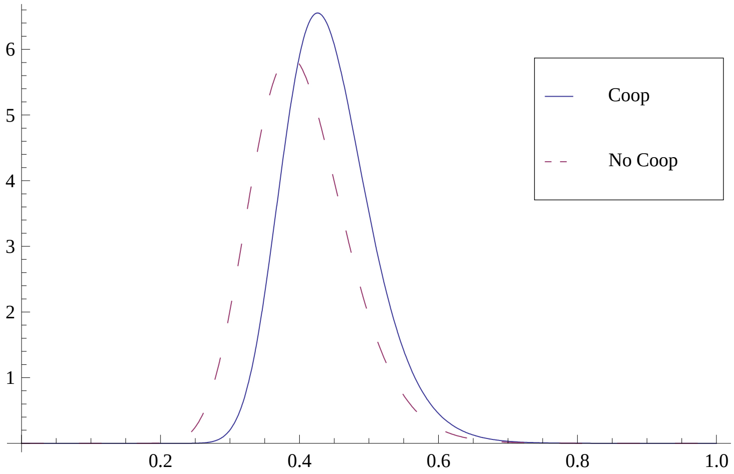

Fig. 6.20 *Active user and Cooperator in Shadowed state*: Lognormal PDF (no cooperation case) and Lognormal-Lognormal PDF (cooperation case)

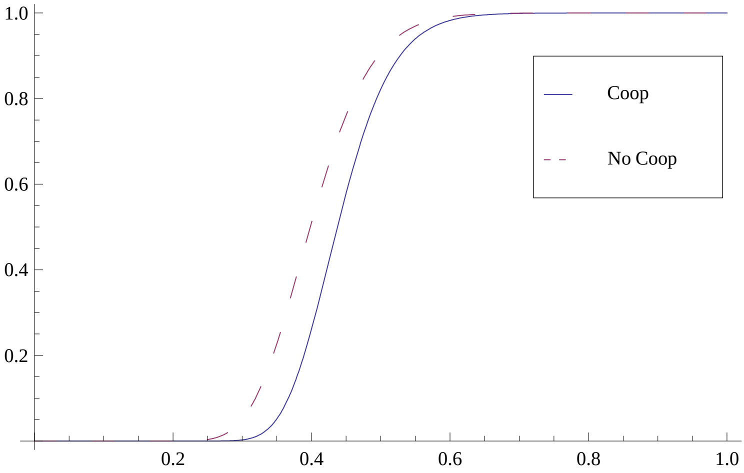

Fig. 6.21 *Active user and Cooperator in Shadowed state*: Lognormal CDF (no cooperation case) and Lognormal-Lognormal CDF (cooperation case)

Chapter 7
Resource Allocation Mechanisms in Satellite Cooperative Systems

Abstract This chapter reports a study concerning the assessment of cooperation effects at MAC layer in DVB-RCS systems. In particular, a modified resource allocation mechanism has been considered in order to implement a *Selective Forwarding* cooperation scheme within a group of sources. The achieved results in terms of *aggregated average throughput* are presented. They confirm those obtained in terms of Bit Error Rate and Packet Error Rate at Physical Layer: the use of cooperation can allow improving system performance depending on the number of cooperators considered and the different channel conditions which they are subject to.

7.1 System Model

The adoption of cooperation is a critical resource allocation issue. In fact, considering a star topology system based on DVB-RCS standard, where a MF-TDMA scheme is employed, a certain number of frequency/time slots are assigned by the Network Control Centre to each user within each superframe depending on the specific demand, through the transmission of the *Terminal Burst Time Plan* (TBTP), which is part of the forward link signalling, [7].

In case of cooperation, a portion of slots have to be reserved for cooperators so that they can retransmit informative users' packets.

Therefore, it is crucial to select the proper allocation mechanism which:

- chooses the part of superframe devoted to cooperation;
- assigns cooperation slots to cooperators;
- associates the cooperators with the active users which, in that particular superframe, need to cooperate.

The proposed model considers a group of sources (also called simply "users" in the following), uniformly distributed in a coverage area, which generate Internet traffic according to an *ON-OFF Model*, as shown in Fig. 7.1, [56]-[57]. In *ON* state, sources emit packets, each one at peak rate ρ while in *OFF* state, they stop any transmission, [58]. The bursty traffic model corresponds to an $M/G/1$ queue, where the inter-arrival time, t_{off}, follows the exponential distribution given by:

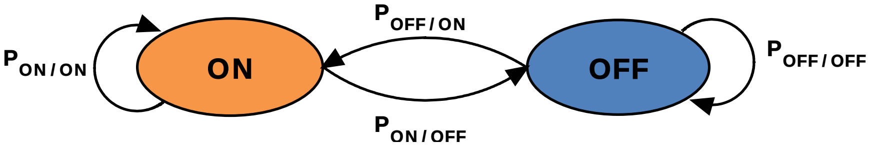

Fig. 7.1 ON-OFF Source Model

$$PDF(t_{off}) = \frac{1}{\mu}\exp(-\frac{t_{off}}{\mu}) \qquad t_{off} \geq 0 \tag{7.1}$$

where μ is the mean of the distribution, while the service time, t_{on}, is Pareto distributed:

$$PDF(t_{on}) = \begin{cases} \alpha\,\frac{\beta^{\alpha}}{t_{on}^{\alpha+1}} & t_{on} \geq \beta \\ 0 & t_{on} < \beta \end{cases} \tag{7.2}$$

where α, which is called *shape*, is an adimensional positive parameter and β, which is called *scale*, is the (positive) minimum possible value of t_{on} and it is, therefore, measured in seconds. As α tends to infinity, the Pareto distribution approaches $\delta(x-\beta)$ where δ is the Dirac delta function.

In this model, sources can be in *ON* state with probability P_{on} given by the following expression, [58]:

$$P_{on} = \frac{\bar{t}_{on}}{\bar{t}_{on} + \bar{t}_{off}} \tag{7.3}$$

wherein $\bar{t}_{on}$ and $\bar{t}_{off}$ the average *ON* and *OFF* time, respectively; and in *OFF* state with probability P_{off} given by:

$$P_{off} = 1 - P_{on} = \frac{\bar{t}_{off}}{\bar{t}_{on} + \bar{t}_{off}} \tag{7.4}$$

For the Pareto distribution, the mean value is expressed in terms of its *shape* parameter, α, and its *scale* parameter, β, as:

$$\bar{t}_{on} = \frac{\alpha}{\alpha - 1}\beta \qquad \alpha > 1 \tag{7.5}$$

Therefore, considering the equations (7.3) and (7.5), the *scale* parameter can be calculated as follows:

$$\begin{aligned}\beta &= \frac{\alpha-1}{\alpha}\cdot\bar{t}_{on}\\ &= \frac{\alpha-1}{\alpha}\cdot\frac{\bar{t}_{off}P_{on}}{1-P_{on}}\\ &= f(P_{on})\end{aligned} \tag{7.6}$$

that is, fixed the values of $\bar{t}_{off}$ and α, β is function of P_{on}.
The set of parameters considered for each distribution is reported in Table 7.1. The peak rate value ρ, is one of peak information bit rates considered in the MF-TDMA scheme for ATM traffic timeslots in the DVB-RCS standard, [8]. In the proposed system model, the resource allocation is done frame by frame; this means that the duration of a superframe is supposed to be equal to that of a frame. Each frame is divided in "logical" timeslots which correspond to a pair of frequency and time values. The bandwidth and duration of all timeslots are assumed equal. The first logical half of each frame is dedicated to the transmission while the second one to the cooperation. However, transmission slots come before cooperation ones in time because cooperators have to receive informative packets by active users in order to be able to cooperate.

OFF	*ON*		
$\mu = \bar{t}_{off}$	α	β (s)	ρ
3.5 s	1.2	$f(P_{on})$	384 kbit/s

Table 7.1 *ON/OFF Model* parameters

7.2 Resource Allocation Mechanism

The adopted resource allocation mechanism is a *fair* procedure, a "round robin" one, in which the same number of timeslots is assigned to users within the group of active users and within the group of cooperators. It is worth noting that:

- the number of timeslot assigned to the two groups can be different, depending on the number of users which demand to transmit in that particular frame;
- the number of users per group can change frame by frame;
- the specific users which belong to two groups can change frame by frame.

Moreover, the association between cooperators and active users is made analysing the *distance matrix*, D, whose dimensions are $N_u \times N_u$ with N_u equal to the total number of sources considered:

$$D = \begin{bmatrix} d_{11} & d_{12} & \dots & d_{1N_u} \\ d_{21} & d_{22} & \dots & d_{2N_u} \\ \vdots & \vdots & \ddots & \\ d_{N_u 1} & d_{N_u 2} & \dots & d_{N_u N_u} \end{bmatrix}$$

where the elements d_{ij} (with $i, j = 1 \dots N_u$) correspond to the distance values between each pair of users belonging to the overall group of considered sources. The choice is performed every frame, by selecting the closest one or two cooperators to each active user, which do not go beyond the predetermined *cooperation threshold* within the coverage area. The selection of one or two cooperators depends on the assumed *cooperation level* which is the maximum number of cooperators fixed a priori in the system.

7.3 System Performance

In order to show the effectiveness of the proposed model and the benefits of the cooperation, several computer simulations have been performed. The considered source model parameters are those which have been defined in Table 7.1 while the other simulation parameters are defined in the following Table 7.2. System performance has been calculated in terms of *aggregated average throughput* for different source loads, as shown in the following graphs.

The *average throughput* for the k-th active user, $\overline{Throughput_k}$, (with $k = 1 \dots N_u$) is given by the following expression:

$$\overline{Throughput_k} = \frac{Throughput_k}{N_{rxframe}} \tag{7.7}$$

where $N_{rxframe}$ is the overall number of received frames in a simulation session while $Throughput_k$ is the overall achieved throughput for the k-th active user which can be written as:

$$Throughput_k = \sum_{j=1}^{N} P_{c_{tslot_j}} \cdot \frac{N_{bit/tslot}}{t_{frame}} \tag{7.8}$$

being $P_{c_{tslot_j}}$ the probability of correct reception of the j-th timeslot, with j from 1 to N which represents the number of timeslots in which the k-th active user has transmitted frame by frame, $N_{bit/tslot}$ the number of bits in a timeslot[1] and t_{frame} the duration of a frame.

The probability of correct reception of a timeslot can be derived from the bit error probability, P_{eb}, calculated at Physical layer, as follows:

---

[1] This value represents the ATM traffic burst size with $N_{atm} = 1$, i.e. 53 Bytes which are equivalent to 424 bits.

$$P_{c_{tslot}} = (1 - P_{eb})^{N_{bit/tslot}} \quad (7.9)$$

The value of P_{eb}, as shown in detail in Chapter 6, depends on the adopted code rate, the E_b/N_0 value, the considered environment (*highway* and *suburban*), the conditions of the LMS channel and the number of cooperators involved in the cooperation. Higher the cooperation level, lower is the value of P_{eb} for a determined environment.

Finally, the *aggregate average throughput*, $\overline{Throughput}_{aggr}$, is defined as the sum of average throughput achieved by all active users:

$$\overline{Throughput}_{aggr} = \sum_{k=1}^{N_u} \overline{Throughput}_k \quad (7.10)$$

The set of parameters used in simulations is reported in Table 7.2.

N_u	$N_{bit/tslot}$	t_{frame}	$N_{timetslot/frame}$	$N_{carrier/frame}$	$N_{tslot/frame}$	E_b/N_0
20	424	0.0265 s	24	8	192	2 dB

Table 7.2 Simulation parameters

The number of timeslots "in time" per frame, $N_{timetslot/frame}$, i.e. the number of time portions available for each carrier per frame, is obtained through the following calculation, considering that each source emits packets at the peak rate ρ:

$$N_{timetslot/frame} = \rho \cdot \frac{t_{frame}}{N_{bit/slot}} \quad (7.11)$$

The total number of logical timeslot per frame is, therefore, given by:

$$N_{tslot/frame} = N_{timetslot/frame} \cdot N_{carrier/frame} \quad (7.12)$$

7.3.1 No cooperation case

In the following, some results concerning the *no cooperation case* are presented. With the term "no cooperation", it is meant the case where sources use the whole frame for transmitting their informative packets and do not require the adoption of a cooperation scheme.

In Fig. 7.2, the aggregate average throughput curves for two considered environments, highway and suburban, and for three different LMS channel conditions are reported. The graph shows as, in both environments, only if the channel is in LOS conditions, the system achieves high values of throughput which approach the system capacity given, in this case, by:

$$C_{nocoop} = \rho \cdot N_{carrier/frame} = 3072\ kbit/s \tag{7.13}$$

whereas, if the channel is in Shadowed or in Blocked state, the system capacity of transmitting packets is pretty zero. Fig. 7.3 and Fig. 7.4 show the throughput performance for the two environments separately, introducing in each graph also the average curve, obtained computing the average of throughput values achieved in the three channel states. The average curve is close to the LOS one because, as already said in Section 6.3, the LOS state is the state with the highest absolute probability (89.22% in the highway environment and 78.31% in the suburban environment).

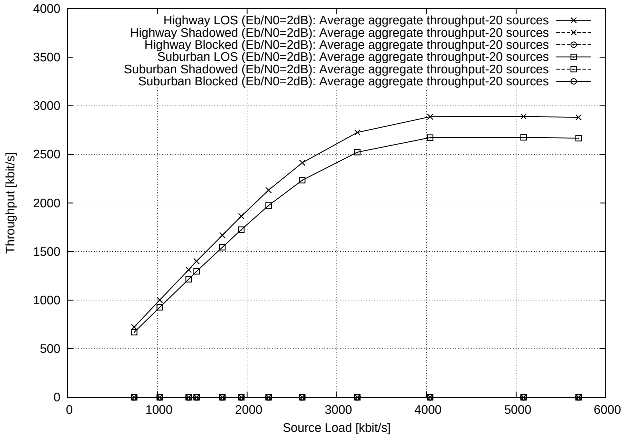

Fig. 7.2 Aggregate average throughput - *No cooperation* case - HIGHWAY and SUBURBAN environments - LOS, Shadowed and Blocked states - 20 sources - $E_b/N_0 = 2\ dB$

7.3.2 Cooperation case

In this Section, the results achieved in the *cooperation case* are reported and analysed. The *cooperation case* encompasses three different cooperative cases:

- *no cooperators* (*cooperation level*= 0)
- 1 *cooperator* (*cooperation level*= 1)
- 2 *cooperators* (*cooperation level*= 2)

The 1 *cooperator* and 2 *cooperators* cases envisage the possibility for each active user to have up to one or two cooperators, depending on the assumed *cooperation level* value. Also the "no cooperators" is considered as cooperation case because, although there are no active cooperators, only half frame is used for transmitting informative

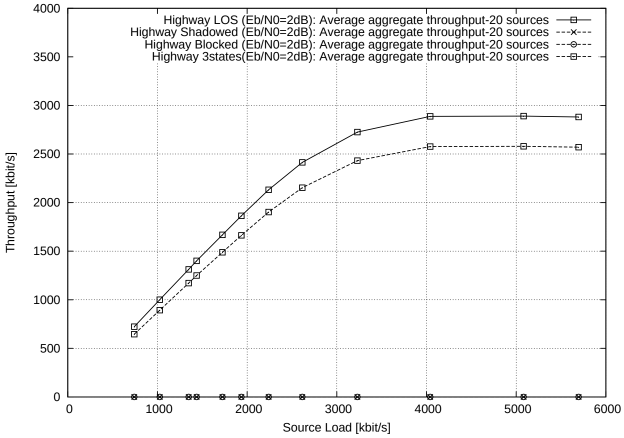

Fig. 7.3 Aggregate average throughput - *No cooperation* case - HIGHWAY environment - LOS, Shadowed, Blocked and 3 states - 20 sources - $E_b/N_0 = 2$ dB

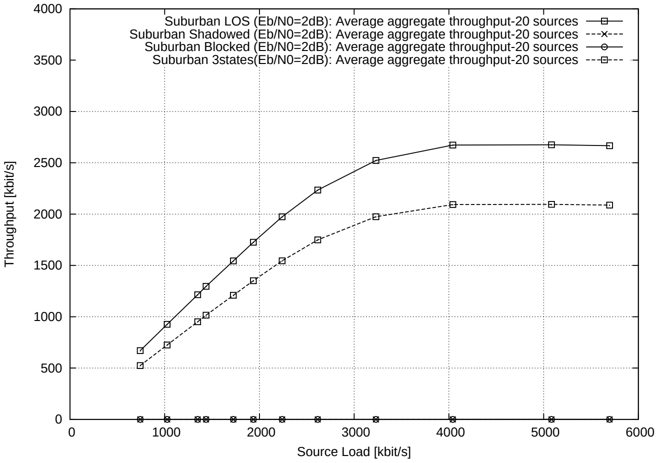

Fig. 7.4 Aggregate average throughput - *No cooperation* case - SUBURBAN environment - LOS, Shadowed, Blocked and 3 states - 20 sources - $E_b/N_0 = 2$ dB

packets.

Fig. 7.5 shows the aggregate average throughput curves in the *no cooperators* case, considering the highway environment and each of the three channel states. As already seen above for the *no cooperation* case, only if the channel is in LOS conditions, the system achieves good values of throughput which, also in this case, approach the cooperative system capacity given by:

$$C_{coop} = \frac{\rho}{2} \cdot N_{carrier/frame} = 1536\ kbit/s \tag{7.14}$$

because only half of every frame is used for the transmission of active users' packets. Also in this case, if the channel is in Shadowed or in Blocked state, the cooperative system capacity is close to zero.

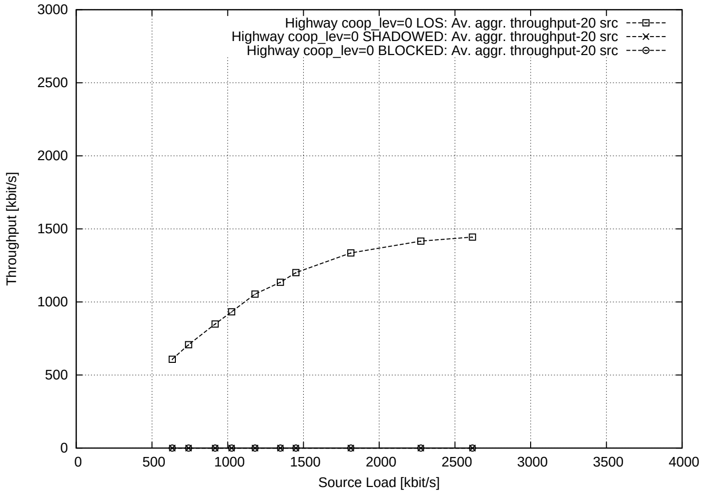

Fig. 7.5 Aggregate average throughput - *Cooperation case, no cooperators* - HIGHWAY environment - LOS, Shadowed and Blocked states - 20 sources - $E_b/N_0 = 2$ dB

Fig. 7.6, instead, considers the 1 *cooperator* case and shows the throughput performance considering all possible combinations of the satellite channel conditions faced by active user and cooperator, in the highway environment. In the graph, the legend reports for each curve the expression "$X-Y$" where X and Y are the channel state encountered by the active user and the cooperator, respectively. In those cases in which at least the active user or the cooperator see the channel in LOS conditions, the system is able to transmit achieving the best values of throughput when both active user and cooperator face the channel in LOS state. Hence, the scenarios wherein the system can transmit data increase in presence of one cooperator.

Similar results can be assessed analysing the 2 *cooperators* case. Fig. 7.7, Fig. 7.8 and Fig. 7.9 report the aggregate average throughput curves achieved in the highway environment when each active user sees the channel in LOS state, Shadowed state and Blocked state, respectively. All possible combinations of the channel conditions faced by 2 cooperators are considered. Also in this case, in the graphs, the legend reports for each curve the expression "$X-Y-Z$" where X, Y and Z are the channel state encountered by the active user, the first cooperator and the second cooperator, respectively. In all cases in which at least either the active user or one of cooperators sees the channel in LOS conditions, the system is able to transmit achieving the best values of throughput when the active user and at least one of cooperators are in LOS state. Hence, if 2 cooperators are involved in the cooperation, the number of scenarios wherein the system can transmit packets increase considerably compared to the *no cooperators* case.

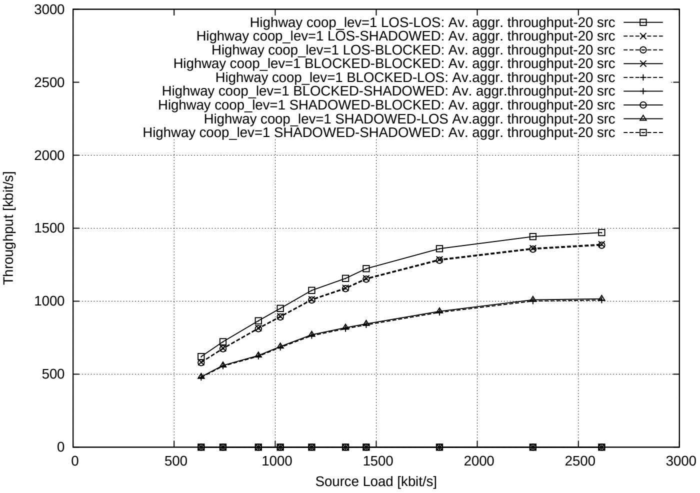

Fig. 7.6 Aggregate average throughput - *Cooperation case,* 1 *cooperator* - HIGHWAY environment - LOS, Shadowed and Blocked states - 20 sources - $E_b/N_0 = 2$ dB

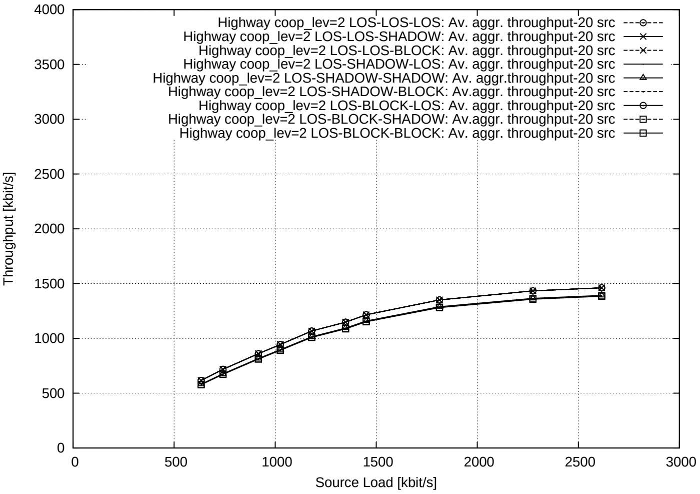

Fig. 7.7 Aggregate average throughput - *Cooperation case,* 2 *cooperators* - HIGHWAY environment - LOS state - 20 sources - $E_b/N_0 = 2$ dB

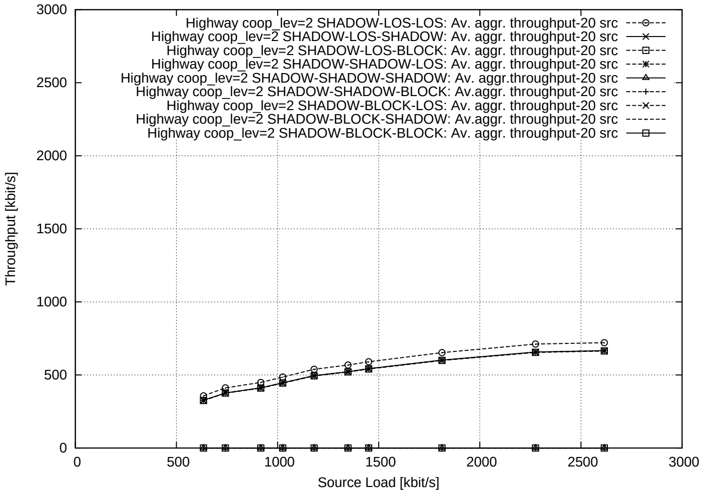

Fig. 7.8 Aggregate average throughput - *Cooperation case,* 2 *cooperators* - HIGHWAY environment - Shadowed state - 20 sources - $E_b/N_0 = 2$ dB

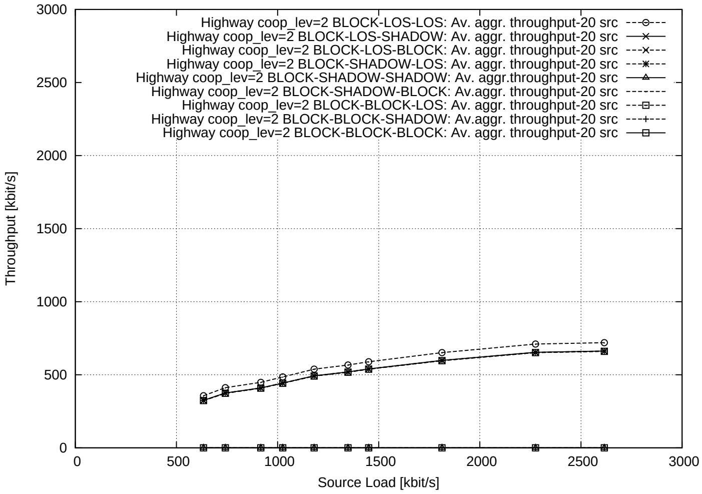

Fig. 7.9 Aggregate average throughput - *Cooperation case,* 2 *cooperators* - HIGHWAY environment - Blocked state - 20 sources - $E_b/N_0 = 2$ dB

Fig. 7.10, Fig. 7.11 and Fig.7.12 show the comparison among the analysed cooperation cases (*no cooperators*, 1 *cooperator* and 2 *cooperators*), and report the aggregate average throughput achieved when the satellite channel seen by sources is in LOS state, in Shadowed state and in Blocked state, respectively. All possible combinations of channel conditions seen by cooperators are taken into account both in the case of 1 *cooperator* and in that of 2 *cooperators*. It is interesting to note that in Fig. 7.10 (sources seeing the channel in LOS state) the curves are very close, regardless of the number of involved cooperators. This happens because active users encounter good channel conditions and their performances are less affected by cooperation. The improvements of performance are, instead, remarkable in the other two cases shown in Fig. 7.11 and Fig.7.12 (sources facing the channel in Shadowed and in Blocked state). In fact, in these cases, the retransmission operated by cooperators becomes fundamental, almost essential, in order to not to lose some pieces of information belonging to the active users.

Finally, the main result is reported in Fig. 7.13 where the throughput curves have been obtained computing the aggregated throughput averaged over sessions where the channel state was only LOS, Shadowed and Blocked. In fact, through this graph, the advantage of using the cooperation, and in particular two cooperators per user, is very noticeable.

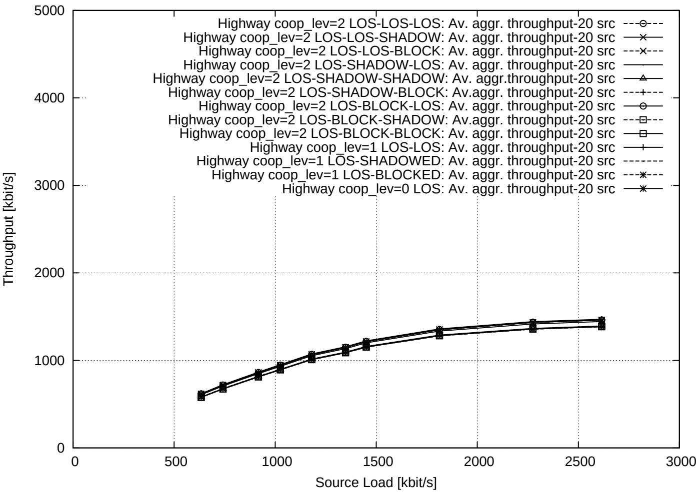

Fig. 7.10 Aggregate average throughput comparison among the *cooperation cases (no cooperators,* 1 *cooperator,* 2 *cooperators)* - HIGHWAY environment, LOS state - 20 sources - $E_b/N_0 = 2$ dB

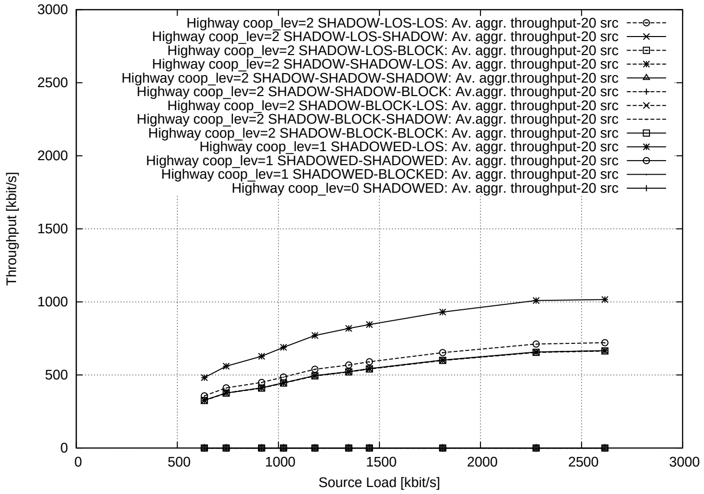

Fig. 7.11 Aggregate average throughput comparison among the *cooperation cases (no cooperators,* 1 *cooperator,* 2 *cooperators)* - HIGHWAY environment, Shadowed state - 20 sources - $E_b/N_0 = 2$ dB

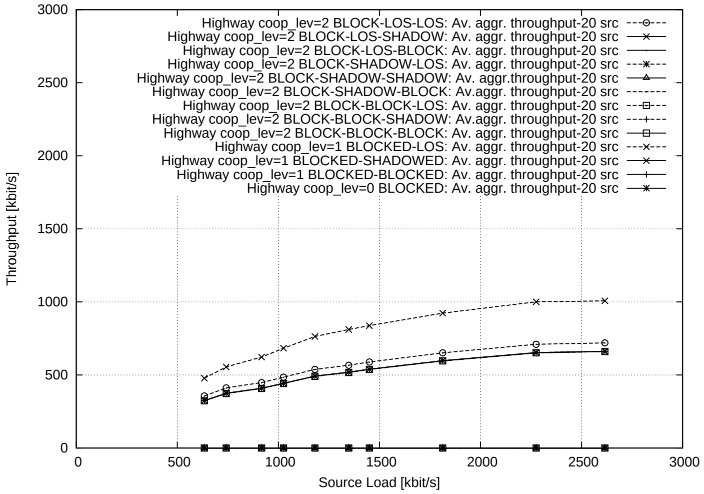

Fig. 7.12 Aggregate average throughput comparison among the *cooperation cases (no cooperators,* 1 *cooperator,* 2 *cooperators)* - HIGHWAY environment, Blocked state - 20 sources - $E_b/N_0 = 2$ dB

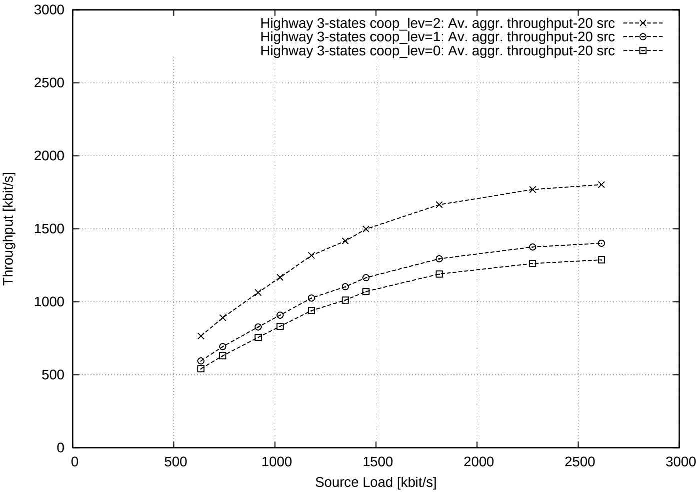

Fig. 7.13 Aggregate average throughput comparison among the *cooperation cases (no cooperators,* 1 *cooperator,* 2 *cooperators)* - HIGHWAY environment, 3 states - 20 sources - $E_b/N_0 = 2$ dB

7.3.3 Comparison No cooperation case-Cooperation case

In the following, a comparison between the *no cooperation case* and the analysed *cooperation cases* (*no cooperators*, 1 *cooperator* and 2 *cooperators*), is reported presenting before the performance in terms of aggregate average throughput achieved when sources see the satellite channel only in LOS state or in Shadowed state or in Blocked state, and then, considering the curves obtained computing the average of throughput values achieved in the three channel states.

Focusing on Fig. 7.14, it is worth noting that when sources see the channel in LOS state, the *no cooperation case* offers the best performance because sources use the whole frame to transmit their informative packets. However, analysing Fig. 7.15 and Fig. 7.16, the gain taken from the cooperation can be appreciated. In fact, without cooperation, the system capacity of transmitting packets is close to zero.

The advantages due to cooperation can be seen, mainly, in Fig. 7.17 which shows the comparison between the curves obtained computing the average of aggregate throughput values achieved in different sessions where the channel state was only LOS, Shadowed and Blocked. This result is very important because, although transmitting in the whole frame allows tolerating higher source loads and, therefore, achieving higher values of throughput, if the system is sized in order to be far from the region of saturation of the cooperative system, the effect of cooperation is remarkable and the case with 2 *cooperators* achieves the best performance, even using only half frame to transmit informative packets.

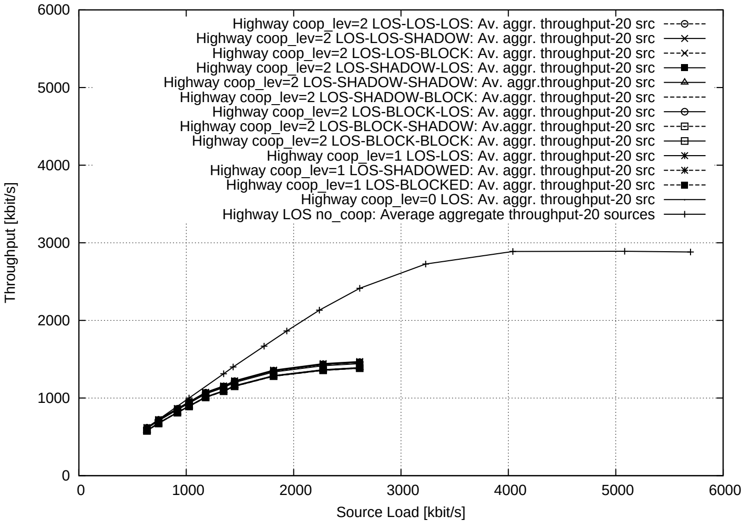

Fig. 7.14 Aggregate average throughput comparison among the *cooperation (no cooperators,* 1 *cooperator,* 2 *cooperators)* and the *no cooperation* cases - HIGHWAY environment, LOS state - 20 sources - $E_b/N_0 = 2$ dB

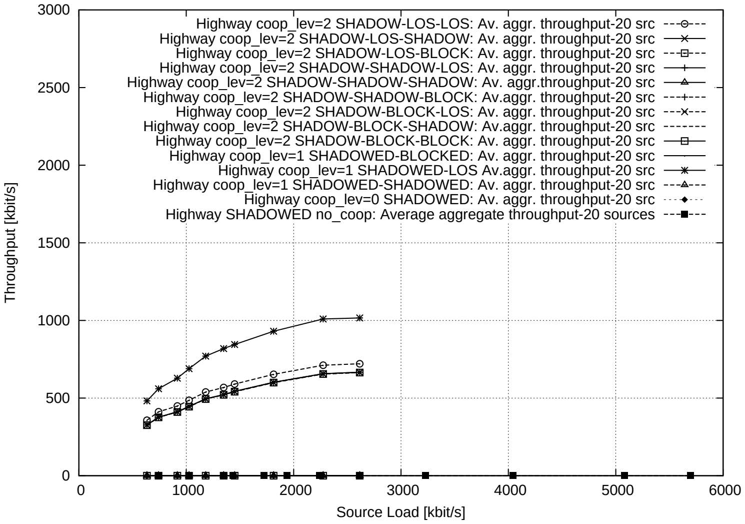

Fig. 7.15 Aggregate average throughput comparison among the *cooperation (no cooperators,* 1 *cooperator,* 2 *cooperators)* and the *no cooperation* cases - HIGHWAY environment, Shadowed state - 20 sources - $E_b/N_0 = 2$ dB

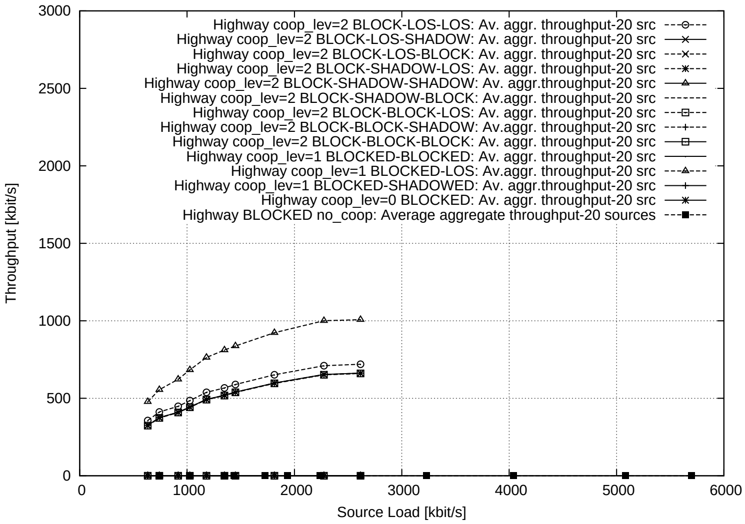

Fig. 7.16 Aggregate average throughput comparison among the *cooperation (no cooperators,* 1 *cooperator,* 2 *cooperators)* and the *no cooperation* cases - HIGHWAY environment, Blocked state - 20 sources - $E_b/N_0 = 2$ dB

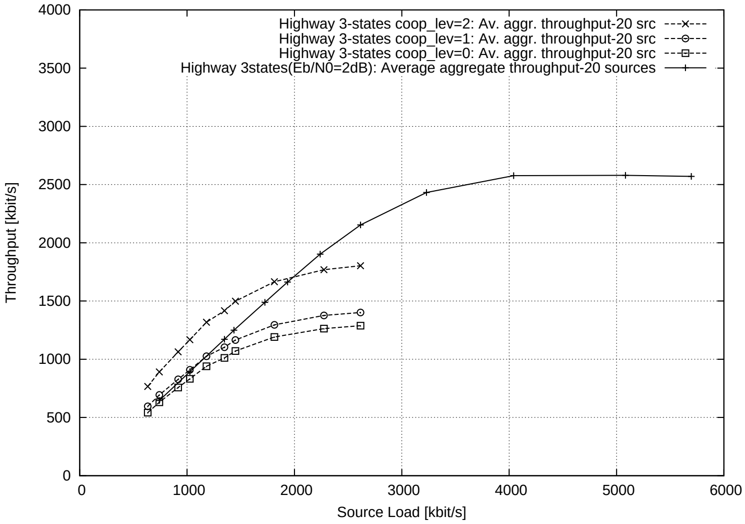

Fig. 7.17 Aggregate average throughput comparison among the *cooperation (no cooperators,* 1 *cooperator,* 2 *cooperators)* and the *no cooperation* cases - HIGHWAY environment, 3 states - 20 sources - $E_b/N_0 = 2$ dB

Part III

Adoption of Cognitive Radio Strategies in Hybrid Satellite-Terrestrial Networks

Chapter 8

Cognitive Radio Approach

Abstract This chapter introduces the *Cognitive Radio* concept, providing an overview on this novel approach. The traditional communication systems which imply an a priori association of the frequency band, the service assigned to it and the used technology, need to become more flexible, efficient and easy-to-use dynamic systems able to cope with the requirements and constraints of the environment and the users. *Cognitive Radio* is an emerging technology which can be considered as a promising and suitable solution to solve this problem. Built on a Software-Defined Radio, *Cognitive Radio* defines an intelligent system which allows a flexible and efficient use of radio spectrum by providing terminals the ability of *sensing* and *dynamic spectrum sharing*.

8.1 Cognitive radio: the last frontier of spectrum exploitation

The continuous demand for bandwidth in wireless communication is generating serious warnings of spectrum saturation both in licensed and unlicensed bands. But the question which arises is: *"the scarcity of spectrum resources is a real issue?"*
Traditional spectrum policy is driven by the general concept of protection of relevant services from interference. The effect is that large portions of spectrum are locked on vast geographical areas for a very long time.
Although this approach has led to the development of many successful services, such as TV broadcasting, cellular networks, wireless access to Internet, etc., it has also introduced a diffused inefficiency in large portions of the radio spectrum. As cited in [59], a report presenting statistics regarding spectrum utilisation, has shown that even during the high demand period of a political convention such as the one held between August 31 and September 1, 2004 in New York City, only about 13% of the spectrum opportunities were utilised, [60].
Moreover, recent studies of the Federal Communications Commission (FCC) Spectrum Policy Task Force have demonstrated that a large amount of licensed bands are

under-utilised [61], i.e. there are a lot of spectral resources which are reserved for specific services, but, actually, they remain unused for most of the time or unused in several locations.

Therefore, the real issue in the spectrum debate appears to be focused more on efficiency in the spectrum usage rather than exploration of new frequencies. This motivates the increasing interest in technologies fully exploiting the available capacity, as it is the *Cognitive Radio*.

Furthermore, this kind of technologies could enable for “Next Generation Networks” (NGNs) services. In the near future, the NGNs will enable a number of key features that can be particularly beneficial to a wide array of potential services. While some of these services can be offered on existing platforms, others benefit from the advanced control, management, and signalling capabilities of NGNs. In particular, the following potential services can be identified:

- **Voice Telephony**: NGNs will likely need to support various existing voice telephony services (e.g. Call Waiting and Call Forwarding).
- **Connectivity Services**: they allow for the real-time establishment of connectivity between endpoints, along with various value-added features (e.g. bandwidth-on-demand, connection reliability, etc.).
- **Multimedia Services**: they allow multiple parties to interact using voice, video, and/or data. This allows customers to converse with each other while displaying visual information.
- **Virtual Private Networks (VPNs)**: voice VPNs improve the interlocation networking capabilities of businesses by allowing large, geographically dispersed organisations to combine their existing private networks with portions of the PSTN, thus providing subscribers with uniform dialing capabilities. Data VPNs provide added security and networking features that allow customers to use a shared IP network as a VPN.
- **Unified Messaging**: it supports the delivery of voice mail, email, fax mail, and pages through common interfaces. Through such interfaces, users will access, as well as be notified of, various message types (voice mail, email, fax mail, etc.), independent of the means of access (i.e. mobile phone, computer, or wireless data device).
- **Information Brokering**: it involves advertising, finding, and providing information to match consumers with providers.
- **E-Commerce**: it allows consumers to purchase goods and services electronically over the network.
- **Call Centre Services**: a subscriber could place a call to a call centre agent by clicking on a Web page. The call could be routed to an appropriate agent, who could be located anywhere, even at home (i.e. virtual call centres).
- **Interactive gaming**: it offers consumers a way to meet online and establish interactive gaming sessions (e.g. video games).

- **Distributed Virtual Reality**: it refers to technologically generated representations of real world events, people, places, experiences, etc., in which the participants and providers of the virtual experience are physically distributed. These services require sophisticated coordination of multiple, diverse resources.
- **Home Manager**: with the advent of in-home networking and intelligent appliances, these services could monitor and control home security systems, energy systems, home entertainment systems, and other home appliances.

All these services will be accessed both from fixed and mobile locations. In the latter case, innovations in wireless communications are essential. The path to next generation wireless communications is characterised by a few but challenging milestones. One of them is, for example, the full IP convergence of all services. Several driving protocols and technologies are ready for the complete abstraction of transport to IP (i.e. VoIP, IP QoS, broadcasting and conferencing services over IP, etc.) but several issues are still open in their integration.

Another key element of future generation systems is the "context awareness" giving access to communications services which are strictly related to current user location and activity. This last step motivates more the adoption of transmission and reception techniques which allow improving system capabilities, like channel coding techniques achieving Shannon-limit, cooperative techniques (as described in the previous Part) and *Cognitive Radio* strategies which allow spectrum reuse and spectrum sharing.

Focusing more on this last topic, the term *Cognitive Radio* (CR) was introduced in [62], with reference to a communication system able to observe and learn from the surrounding environment as well as to implement and adapt its own transmission modes to user requirements. The concept of *Cognitive Radio* is originated from the contrast between an increasing demand of broadband services and the scarcity of radio resources. From various studies, as those cited before, the possibility of a CR system is envisaged, i.e., as defined by Haykin in [63], "*an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g. transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind:*

- *highly reliable communications whenever and wherever needed;*
- *efficient utilization of the radio spectrum.*"

Summarising, seven key words can characterise a CR system, [63]:

1. *awareness*
2. *intelligence*
3. *learning*
4. *adaptivity*

5. *reliability*
6. *efficiency*
7. *reconfigurability*

More specifically, a CR system is able to, [64]-[65]:

- determine which portions of radio spectrum are available in a given temporal interval and in a given location (*free spectrum holes*, see Fig. 8.1);
- detect the presence of licensed users, by sensing the electromagnetic environment (*spectrum sensing*);
- select the best available channel (*spectrum management*);
- coordinate the access to the selected channel with other users (*spectrum sharing*);
- vacate the channel when a licensed user is detected and its own transmission produces a damaging interference (*spectrum mobility*).

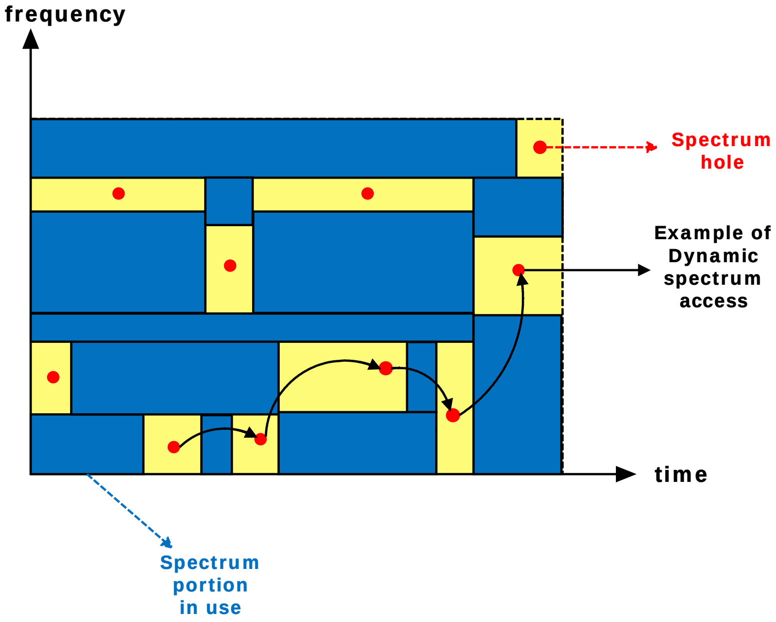

Fig. 8.1 Example of dynamic spectrum access

The search for available resources is not limited to spectrum portions dedicated to unlicensed communications, but is also extended to licensed bands. In such a context, the *Cognitive Radio* system, called *secondary* system, must coexist and, therefore, share the spectrum, [66], with a *primary* system, which is the license owner, without producing harmful interference, as shown in Fig. 8.2. The *secondary* terminals can perform an *overlay spectrum sharing* or an *underlay spectrum sharing*. In the first case, CR terminals use only portions of spectrum not exploited by licensed users, in order to minimise interference to the *primary* system, while in the second one, CR terminals use also spectrum portions exploited by the *primary* users which consider the *secondary* transmissions as noise. In this case, it is mandatory not to exceed the interference threshold in order not to impair the licensed transmissions.

Both terrestrial and satellite systems can be considered for the role of primary and secondary users.

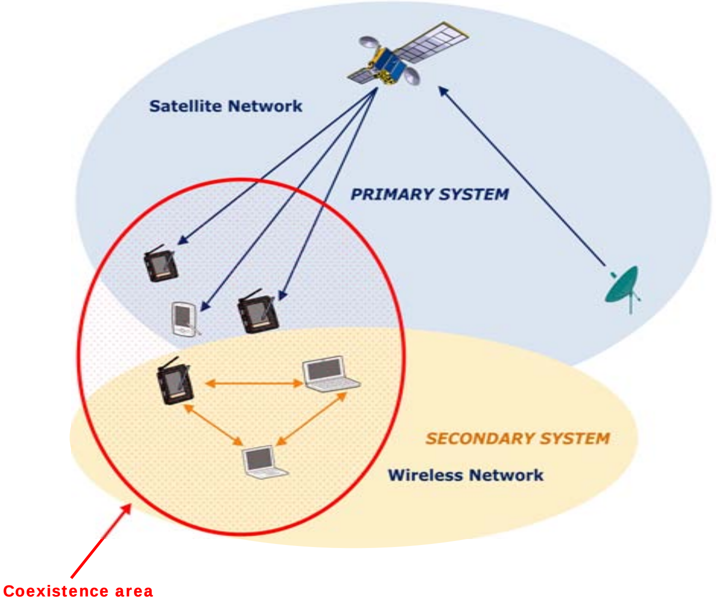

Fig. 8.2 Example of coexistence scenario

In case of absence of primary users, instead, CR users have the same right to access the radio resources. Therefore, sophisticated *spectrum sharing* methodologies are required for CR users to compete for the unlicensed band portions.

The CR capability of *reconfigurability* is provided by a platform known as Software-Defined Radio (SDR), upon which a CR system is built, [67]-[68]-[69]. A CR system, in fact, assumes that there is an underlying system hardware and software infrastructure that is able to support the flexibility demanded by cognitive algorithms [70]. In this case, the abstraction of hardware capabilities for radio software architecture is a primary design issue because is desirable to isolate the cognitive engine from the underlying hardware. In such a context, the SDR represents the essential enabling technology for the characteristics which offers. This methodology allows the development of applications in a consistent and modular fashion such that both software and hardware components can be promptly reused for different implementations. SDR technology can also provide an advanced management of the available resources and facilitate the definition of interfaces for the coexistence of different communication services.

8.2 Open issues on Cognitive radio technologies

The *Cognitive Radio* idea of exploiting the unused frequency bands is really powerful and efficient by the point of view of flexibility in spectrum management. Moreover, also the use of licensed frequencies by *secondary* users in a “transparent” way to *primary* users is a challenging aspect in wireless communications. With the term “transparent”, it is meant that the *Cognitive Radio* terminals do not impair communications of licensed users.

In particular, it is possible to address three main issues that make this challenge absolutely not trivial.

The first issue concerns the *spectrum sensing* and the detection of *primary* licensed users. This operation is mandatory for CR terminals in order to determine the presence or not of licensed users. *Spectrum sensing* can be performed estimating the noise temperature over a certain range of frequencies, determining eventual variations due to the presence of *primary* users. However, it cannot be done while transmitting data. Therefore, *secondary* users should stop their transmissions while sensing, decreasing the spectrum efficiency. A trade-off between spectrum efficiency and sensing accuracy is necessary and the development of new sensing algorithms which minimise the sensing time for a given sensing accuracy, required, [64].

Another critical issue in this context is determining how CR terminals access to spectrum holes. Indeed, if a frequency band is detected unoccupied after sensing, there will be a strong interference if all secondary users try to access to the free resource at the same time.

For this reason, it is fundamental to define the role of a *Cognitive Manager* (CM) which coordinates the CR terminals access and decides how the available resources are managed and allocated. In particular, a set of suited multiple access criteria for *spectrum sharing* must be defined in order to have an efficient and enhanced use of the radio spectrum. An important task is to define the location of the cognitive decisional functions which can be implemented in a *centralised* or *distributed* network architecture. In particular, *Cognitive Manager*s can work in three operational modes:

- *Centralised* mode, where the CMs in each CR nodes execute locally the radio access directives coming from the CM located in a central entity which controls the spectrum allocation and access procedures.

- *Coordinated* mode, where the CMs in each CR nodes perform local independent decisions on spectrum resources, exploiting, however, side coordination information coming from the CM in the central entity.
- *Distributed* mode, where the CM of each node operates through competitive independent decisional models.

Different *spectrum sharing* strategies can be found in literature, [71], [72], [73]. Some of these are based on *heuristic* methods which are more immediate to be applied even if not optimal while others use the *Game Theory*, which is a powerful mathematical tool able to manage complex communications contexts.

Finally, a third issue concerns the amount of information required to realise a coordination between CR terminals. In this case, a trade-off between a complete information describing opportunely the environment of each CR terminal and a partial information which gives to CR terminal a less accurate description of the operating environment but, at the same time, produces less overhead, has to be found.

8.3 Standardisation efforts on Cognitive radio

Cognitive Radio concept encompasses many different aspects not only technical but also managerial and financial including those related to the development of Software-Defined Radio. For these reasons, there is a strong need to standardisation in this area. A coordination among regulators, academic sector and product developers is also required. Realising the importance of a coordinated work around *Cognitive Radio* standardisation, the IEEE created the *IEEE Standards Coordinating Committee (SCC) 41* on Next Generation Radio and Spectrum Management, [74]-[75].

IEEE SCC41 was preceded by the IEEE 1900 task force, which initiated the IEEE standards setting effort in this area. The task force was started in the first quarter of 2005, jointly by the IEEE Communications Society and the IEEE Electromagnetic Compatibility Society. On March 22, 2007 the IEEE Standards Board approved the reorganisation of the IEEE 1900 effort as Standards Coordinating Committee 41 (SCC41) for Dynamic Spectrum Access Networks (DySPAN). The IEEE Communications Society and Electromagnetic Compatibility Society are sponsoring societies for this effort, as they were for the IEEE 1900 effort.

IEEE SCC41 is divided into six working groups (WGs), each responsible for evolving standardisation processes for different aspects of *Cognitive Radio*. Working groups are identified as IEEE 1900.x, where ".x" represents the different number which identifies the WG. They are, [74]:

1. IEEE 1900.1 Working Group on *Terminology and Concepts for Next Generation Radio Systems and Spectrum Management*: the purpose of this WG is to develop a standard which will facilitate the development of spectrum management, pol-

icy defined radio, adaptive radio, software-defined radio, reconfigurable radio and networks technologies, by clarifying the terminology and how these technologies relate to each other.
2. IEEE 1900.2 Working Group on *Recommended Practice for Interference and Coexistence Analysis*: this WG aims at producing a standard which provides technical guidelines for analysing and measuring the interference between radio systems operating in the same frequency band or between different frequency bands in order to provide some criteria for the potential coexistence among systems.
3. IEEE 1900.3 Working Group on *Recommended Practice for Conformance Evaluation of Software Defined Radio Software Modules*: the mandate of this WG is developing test methods for conformance evaluation of software for SDR devices. Moreover, it aims at defining a set of recommendations that help in assuring the coexistence and compliance of the software modules of CR devices before proceeding toward validation and certification of the final devices.
4. IEEE 1900.4 Working Group on *Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks*. From April 2009, this WG works on two projects:
    - 1900.4*a*: this project deal with the writing of a standard amendment on *Architecture and Interfaces for Dynamic Spectrum Access Networks in White Space Frequency Bands*.
    - 1900.4.1: this project works on the standard for *Interfaces and Protocols Enabling Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Networks*.
5. IEEE 1900.5 Working Group on *Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access Applications*: the purpose of this WG is to define a policy language (or a set of policy languages or dialects) to specify interoperable, vendor-independent control of CR functionality and behavior for Dynamic Spectrum Access resources and services.
6. IEEE 1900.6 Working Group on *Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and other Advanced Radio Communication Systems*: the target of this WG is to make development and evolution of spectrum sensors independent of the development and evolution of other system functions. The resulting standard will provide a formal definition of data structures and interfaces for exchange of sensing related information.

In addition to this strong standardisation effort, other IEEE groups are involved in the development of air interface standard based on *Cognitive Radio* concept. In particular, the IEEE 802.22 WG is working on a standard about the Physical and MAC layers of Wireless Regional Area Networks (WRAN) using white spaces in the TV frequency spectrum, [76]-[77]-[78].

The IEEE 802.22 WRAN standard uses *Cognitive Radio* techniques to allow sharing, on a non-interfering basis, geographically unused spectrum bands which are allocated to the Television Broadcast Service, in order to bring broadband access to low population density areas such as rural environments. The CR strategies implemented in the standard ensure that no harmful interference is caused to the licensed operations (i.e. digital TV and analog TV broadcasting) and to low-power licensed devices such as wireless microphones.

The standard is expected to be finalised in the first quarter of 2010.

Chapter 9
Resource Allocation in Cognitive Radio Networks

Abstract This chapter shows the potential benefits coming from the adoption of a *Cognitive Radio* strategy in a context of coexistence of two systems. The first system, called *primary* system, has the license to operate in a certain spectrum band while the second one, named *secondary* system, does not have a license to work in a desired band but, being "cognitive", it can share radio spectrum resources with the licensed one. This can happen if the cognitive device is able to use efficiently the radio spectrum, without interfering with the licensed communication service. Therefore, a resource allocation strategy for *spectrum sharing* is evaluated for the *secondary* system considering two application scenarios: a fully terrestrial context and a mixed satellite/terrestrial environment.

9.1 System Model

A *Cognitive Radio* system is composed by a *secondary* system which have to coexist with a *primary* system, which is the license owner, without producing harmful interference, as described in previous Chapter.

In this study, the problem is formalised as a constrained maximum search, where the objective function is the rate of the *secondary* system which is subject to the preservation of the *primary* system quality requirements.

All the considered systems are OFDM based. Several reasons induce to consider OFDM as the principal candidate for implementing the physical layer of a *Cognitive Radio* system, ranging from its ability to combat multipath fading to a relatively simple way to manage spectrum occupancy.

A schematic representation of a basic *Cognitive Radio* system model is depicted in Fig. 9.1, where the transmitters (T_1 and T_2) and the receivers (R_1 and R_2) of both systems and the coefficients of the channel matrix C, can be identified.

In particular, let $P_{Rx}(k)$ and $P_{Tx}(k)$ be the received and the transmitted power on the

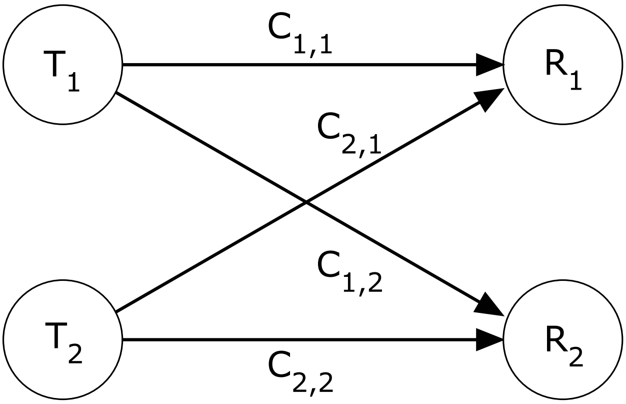

Fig. 9.1 *Cognitive Radio* system model

kth carrier of the system, $k = 0, 1, \ldots, K-1$, with K total number of carriers, $C(k)$ the instantaneous channel matrix of dimensions 2x2, relative to the kth channel and N_x the noise power. The index x stands for either 1, denoting the *primary* system, or 2, denoting the *secondary* system.

The adopted cognitive strategy is derived for a *secondary* system able to collect all the relevant propagation information of both systems. The power vector transmitted by the *primary* system, the channel impulse response and the statistical measures of the thermal noise are supposed known by the *secondary* system. This is a strong hypothesis because, in reality, the *secondary* system can only estimate such values but not know them exactly. However, such a complete knowledge is assumed in this investigation.

The considered system is regulated by the following equations, (9.1) and (9.2), where k is the carrier index:

$$P_{R1}(k) = C_{1,1}(k)P_{T1}(k) + C_{2,1}(k)P_{T2}(k) + N_1(k) \tag{9.1}$$

$$P_{R2}(k) = C_{1,2}(k)P_{T1}(k) + C_{2,2}(k)P_{T2}(k) + N_2(k) \tag{9.2}$$

The solution space is represented by the $P_{T2}(k)$ power vector, obtained by the *Cognitive Radio* strategy.

The problem can be formulated as a constrained multi-variable maximum search, where the objective function, namely R, is the *secondary* system bit rate and the constraints are given by the minimum quality, in terms of maximum tolerable BER that must be assured for the *primary* and the *secondary* systems.

The objective function and the constraints are given by:

$$\max_{b_2(k)} R = \sum_{k=0}^{K-1} b_2(k) \tag{9.3}$$

$$\frac{P_{T2}(k)C_{2,2}(k)}{N_2(k) + P_{T1}(k)C_{1,2}(k)} \geq SINR_{R2,min}(b_2(k)) \tag{9.4}$$

$$\frac{P_{T1}(k)C_{1,1}(k)}{N_1(k) + P_{T2}(k)C_{2,1}(k)} \geq SINR_{R1,min} \tag{9.5}$$

$$\sum_{k=0}^{K-1} P_{T2}(k) \leq P_{T2,tot} \tag{9.6}$$

In the (9.3), $b_2(k)$ indicates the value of the *secondary* bit rate for the *k*th carrier. This is equal to 0 if the considered carrier is not used by the *secondary* system. Otherwise it assumes a value depending on the used modulation.

Constraints (9.4) and (9.5), instead, are derived according to the signal-to-noise-and-interference ratio (*SINR*) at the *secondary* and *primary* receiver, respectively. Let $SINR_{R1,min}$ and $SINR_{R2,min}(b_2(k))$ be the minimum *SINR* values that allow a reliable communication, i.e., values that allow a given BER to be achieved, on a given carrier of the *primary* and *secondary* system, respectively. It is assumed that an adaptive modulation is used for the *secondary* system, so that the quantity $SINR_{R2,min}(b_2(k))$ is a function of the number of bits delivered by the *k*th carrier, i.e., the modulation scheme used on the carrier (to be chosen from a given set). The *primary* receiver target quality, instead, is expressed by a given value of $SINR_{R1,min}$, which results independent of $b_2(k)$ because a QPSK modulation scheme is assumed to be used by the *primary* system.

During the proposed allocation process, the simplest modulation scheme is considered first (e.g. QPSK) to compute $SINR_{R2,min}$, and then, whenever possible, a modulation upgrade, which increases the modulation order, is performed recursively (for further details see the dynamic power allocation algorithm described in Section 9.1.1).

According to the constraints (9.4) and (9.5), the power on the *k*th carrier of the *secondary* system is upper and lower bounded by the following expressions:

$$P_{T2}(k) \leq \frac{P_{T1}(k)C_{1,1}(k) - N_1(k)SINR_{R1,min}}{SINR_{R1,min}C_{2,1}(k)} \tag{9.7}$$

$$P_{T2}(k) \geq \frac{SINR_{R2,min}(P_{T1}(k)C_{1,2}(k) + N_2(k))}{C_{2,2}(k)} \tag{9.8}$$

Finally, the constraint in (9.6) is the total amount of power transmitted by the *secondary* device. This is ruled by (9.6) and derived from regulatory limitations on the *secondary* transmission power.

The described constraints can, sometimes, be contradictory: if this happens, the applied rule is to protect the *primary* service.
As what concerns the quality constraint of the *primary* system, it is worth noting that for each carrier k, two possible cases may occur at the *primary* receiver. Let $SINR_{R1,2off}$ be the signal-to-noise ratio experienced at the *primary* receiver before the *secondary* begins its transmission. The two possible cases are:

$$SINR_{R1,2off}(k) < SINR_{R1,min} \tag{9.9}$$

$$SINR_{R1,2off}(k) \geq SINR_{R1,min} \tag{9.10}$$

In the former case, (9.9), the *primary* system does not reach the desired quality level on the kth carrier, so the *primary* does not use the carrier whereas the *secondary* system can fully exploit it. In the latter case, (9.10), the *primary* system reaches the desired minimum *SINR* and it, eventually, provides an useful margin to be exploited by the *secondary* system.

9.1.1 Dynamic Power Allocation Strategy

The adopted *Cognitive Radio* strategy is based on a heuristic method an it is able to cope with the coexistence problem of different services and systems in the same radio spectrum portions.
The underlying idea of the proposed resource allocation strategy is the creation of a power allocation vector for the *secondary* system, iteratively updated until a stop condition is reached, i.e. when the total amount of *secondary* power is reached or a constraint is violated or, anyway, when the maximum number of possible iterations is reached. In fact, it is possible to evaluate the maximum number of iterations which the algorithm can perform.
The allocation procedure is an iterative process where the instantaneous *secondary* resources at iteration n are represented by two vectors, an integer vector $b^{(n)}$ and a real valued vector $P_{T2}^{(n)}$, representing, respectively, the used modulation scheme and the allocated power for all the K carriers. The possible values of $b(k)^{(n)}$ are $\{0,2,4,6\}$ which identify a non-allocated carrier, a QPSK, a 16QAM and a 64QAM modulation scheme on the kth carrier, in that order. An auxiliary vector $d^{(n)}$ represents the amount of power, at iteration n, necessary to increase the rate of the *secondary* system on each carrier. The rate increments are those that, if applied, change the corresponding value of $b(k)$ from 0 to 2 (activation of the carrier with a QPSK modulation), from 2 to 4 (modulation upgrade from QPSK to 16QAM), from 4 to 6 (modulation upgrade from 16QAM to 64QAM).
Such an algorithm will stop anyway, at maximum after achieving the maximum number of iterations which can be estimate as the product between the total number of

carriers K and the number of rate increments which can happen during the process and which change the modulation order, M. In the proposed strategy, M is equal to 3 because there are three possible changes corresponding to the activation of the carrier with a QPSK modulation, the upgrade from QPSK to 16QAM modulation and upgrade from 16QAM to 64QAM modulation.
The algorithm is performed as follows:

- **Step 0**: $n = 0$, $b^{(0)}$ and $P_{T2}^{(0)}$ are initialised to all-zero vectors of length K (no carriers allocated to the *secondary* system).
- **Step 1**: $d^{(n)}$ is computed taking into account the constraints in (9.7) and (9.8), as well as the current allocation $b^{(n)}$ and $P_{T2}^{(n)}$. The carriers where the lower power constraint is greater than the upper one are marked as “unusable”.
- **Step 2**: find the carrier for which a rate increment is possible with the lowest amount of *secondary* power, i.e. $\hat{k} = \arg\min_k d(k)^{(n)}$ (excluding the unusable carriers and those already allocated with the highest modulation order).
- **Step 3**: if a valid $\hat{k}$ is found, allocate the carrier by defining the modulation scheme:

$$b^{(n+1)}(k) = \begin{cases} b^{(n)}(k) + 2 & \text{if } k = \hat{k}, \\ b^{(n)}(k) & \text{otherwise.} \end{cases}$$

  and the corresponding power:

$$P_{T2}^{(n+1)}(k) = \begin{cases} P_{T2}^{(n)}(k) + d(k)^{(n)} & \text{if } k = \hat{k}, \\ P_{T2}^{(n)}(k) & \text{otherwise.} \end{cases}$$

  .
- **Step 4**: increase the iteration index n.
- **Step 5**: compute the total amount of power allocated to the *secondary*; if

$$\sum_{k=1}^{K} P_{T2}^{(n)}(k) \leq P_{T2,tot}$$

  than go back to **Step 1**, otherwise use the allocation vectors $b^{(n)}$ and $P_{T2}^{(n)}$.

It is worth noting that, at each iteration, there are two possible choices: allocating a new carrier to the *secondary* with a QPSK modulation or performing a modulation upgrade (e.g. QPSK to 16QAM or 16QAM to 64QAM) on a carrier already allocated to the *secondary* service. These choices are equivalent in term of rate increment and it is selected that one with the minimum required power.

9.2 Application Scenarios

Cognitive Radio strategies are strictly related to their operating environment. In this section, two scenarios are taken into account: a fully terrestrial and a mixed satellite/terrestrial scenario. The considered scenarios have the objectives to investigate on the coexistence problem, following the model illustrated previously. A terrestrial infrastructure or a satellite system considered as *primary* systems, have to coexist with a *secondary* mesh-based terrestrial telecommunication service. All the considered systems are OFDM based, but they exhibit different propagation conditions.

9.2.1 Fully Terrestrial Context

In the first scenario, both the *primary* and the *secondary* are terrestrial systems and are characterised by a single transmitter and a single receiver. The two systems are not independent since they share the same radio resources. The signal from each transmitter represents an interfering component to the other system receiver. The *secondary* system operates in OFDM mode with the same carrier spacing as the *primary* one. It has, however, a more flexible power allocation scheme. Being *cognitive*, the operating parameters like frequency, modulation and power are modified by its software radio implementation. The possible modulations for the considered *secondary* system are QPSK, 16QAM and 64QAM. With a constant bit error probability, the minimum required signal-to-noise ratio depends on the modulation order. The actual transmission scheme is automatically selected by the *secondary* device depending on the available sensed information and the outcomes of the allocation strategy described before.

9.2.1.1 Channel Model

In both systems, the received signal is corrupted by different phenomena: a *path loss* term due to the distance between transmitter and receiver calculated at the middle-band frequency, and a *multipath* fading due to the propagation environment and terminal motion. The path loss is modelled by:

$$L_{terr} = 10 log_{10} \left(\frac{4\pi d}{\lambda_0} \right)^{\alpha} dB \tag{9.11}$$

where the exponent α models the attenuation dependence from the distance, λ_0 is the central frequency wave length and d is the distance between transmitter and receiver. In the time-domain the channel exposes a finite impulse response of L samples, resulting in a frequency selective channel response. A *tapped-delay line* model with

Rayleigh distributed coefficients is adopted:

$$h(t,\tau) = \sum_{n=0}^{L-1} \alpha_n \delta(t-\tau_n) \tag{9.12}$$

where τ_n is the delay of echo n and α_n is the complex channel coefficient of n-th echo. The power delay profile is exponential and can be expressed as follows:

$$\sigma_n^2 = e^{-\beta n} \tag{9.13}$$

where σ_n^2 is the variance of the n-th coefficient and β is computed for a normalised mean power response.

9.2.2 Mixed Satellite/Terrestrial Context

Differently from the previous case, the second scenario is mixed, i.e. it is characterised by a licensed *primary* satellite system and a *secondary* terrestrial system. The *primary* one is a mobile satellite system based on DVB-SH standard [9]-[10], while the *secondary* one is a wireless terrestrial system with the same characteristics of that described above. Both systems work in L band (0.39-1.55 GHz) and exploit a context of coexistence in which the *secondary* one is allowed taking resources from another system without interfering in its normal operations. Each system is assumed to be characterised by a single transmitter and a single receiver.

9.2.2.1 Channel Model

The propagation channel for the considered mobile satellite channel at L band is the *Lutz* model, [79]. Such a model is based on a two-states (*GOOD-BAD*) Markov-chain for the characterisation of the fading process. According to this class of models, the amplitude of the fading term is divided into fast and slow fading. Slow fading events, normally due to large obstacles, are modelled as a finite state machine. Fast fading events, due to the irregularity of the obstacles and to the multipath propagation phenomenon can be additionally represented as superimposed random variations that follow a given probability density function for each state.

In particular, the *GOOD* state is characterised by the absence of shadowing and the presence of a direct signal component. The total received signal, in this case, follows a Rician PDF given by:

$$p_{rice}(S) = ce^{-c(S+1)} I_0(2c\sqrt{S}) \tag{9.14}$$

where S is the received signal power, c is the *Rice Factor*, i.e. the direct-to-multipath signal power ratio and I_0 is the modified Bessel function of order zero.

In the *BAD* state, instead, no direct signal path exists and the multipath fading is characterised by a Rayleigh process with short-term mean received power S_0. The PDF of the received power conditioned on S_0 is given by:

$$p_{ray}(S|S_0) = \frac{1}{S_0}\exp(S/S_0) \tag{9.15}$$

The slow shadowing process results in a time varying S_0 for which a Lognormal distribution is assumed:

$$p_{LN}(S_0) = \frac{10}{\sqrt{2\pi}\ln 10}\cdot\frac{1}{S_0}\exp\left[\frac{(10\log S_0-\mu)^2}{2\sigma^2}\right] \tag{9.16}$$

where μ is the mean power level decrease (in dB) and σ^2 is the variance of the power level due to shadowing.
The overall received signal power PDF is got by the combination of (9.14), (9.15) and (9.16) and can be expressed as follows:

$$p(S) = (1-A)\cdot p_{rice}(S) + A\cdot\int_0^\infty P_{ray}(S|S_0)p_{LN}(S_0)\,\mathrm{d}S_0 \tag{9.17}$$

where A is the time-share of shadowing. The values of the parameters A, c, μ and σ for different environments can be found in [79].
This channel, differently from the previous one, has a flat frequency response.
Also in this case, a *path loss* term, due to the distance between transmitter and receiver, is considered:

$$L_{sat} = 10log_{10}\left(\frac{4\pi d}{\lambda}\right)^{\alpha} dB \tag{9.18}$$

where the exponent α models the attenuation dependence from the distance, λ is the central frequency wave length and d is the distance between transmitter and receiver.

9.3 System Performance

In the following, the proposed *Cognitive Radio* strategy is validated through computer simulations for both considered scenarios. The terrestrial propagation exponent (α) is considered equal to 3, valid for a medium density urban environment while, for the satellite component, the value of α is assumed equal to 2. Moreover, the number of carriers K is fixed equal to 128 for the fully terrestrial scenario and to 853 for the mixed satellite/terrestrial one.

9.3.1 Fully Terrestrial Context

The performance for the fully terrestrial scenario have been evaluated considering, as the main performance index, the achieved rate of the *secondary* system.
Simulations have been conducted for six target BER values of the *secondary* system, from 10^{-3} to 10^{-8} and for three E_b/N_0 values for the *primary* receiver equal to 10 dB, 15 dB and 20 dB. It is worth highlighting that the achieved *primary* rate depends only on the *primary* received E_b/N_0, since the *Cognitive Radio* strategy always preserves the *primary* rate.
The considered context has terminal displacements as shown in Fig. 9.2 and in Fig. 9.3. Units are normalised to the *primary* distances.

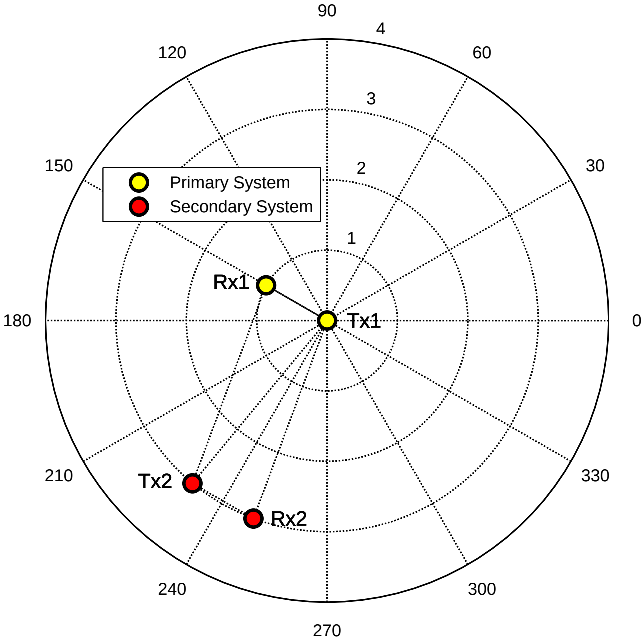

Fig. 9.2 Fully terrestrial terminals displacements: case A

The performance of the *secondary* system heavily depend on its target BER and the *primary* working point. In Fig. 9.4 and in Fig. 9.5, for both considered terminals displacements and each E_b/N_0 value of the *primary* working points, the BER values in log-scale function of the achieved *secondary* rate are reported.
In the first case (Case A), i.e. where the *secondary* terminals are further from the *primary* system, it is worth noting that, for a fixed BER, the achieved *secondary* rate increases as the *primary* E_b/N_0 increases. This is a well known limitation of *Cognitive*

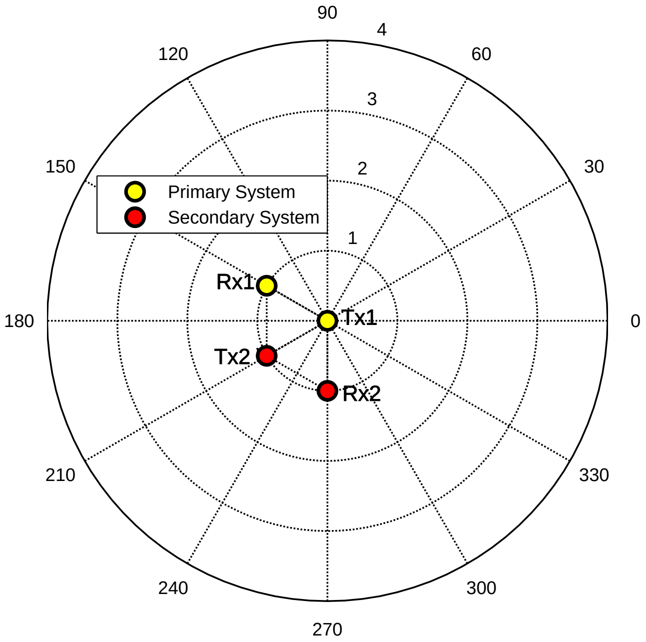

Fig. 9.3 Fully terrestrial terminals displacements: case B

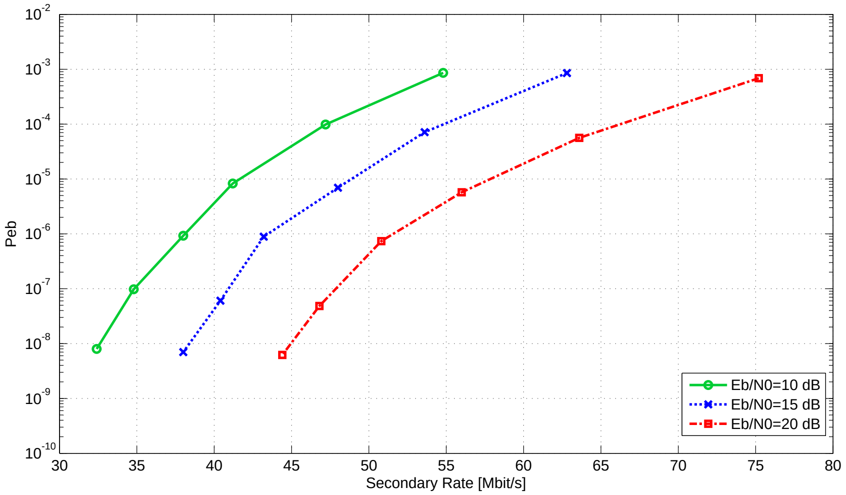

Fig. 9.4 BER vs. *Secondary* Rate: Case A

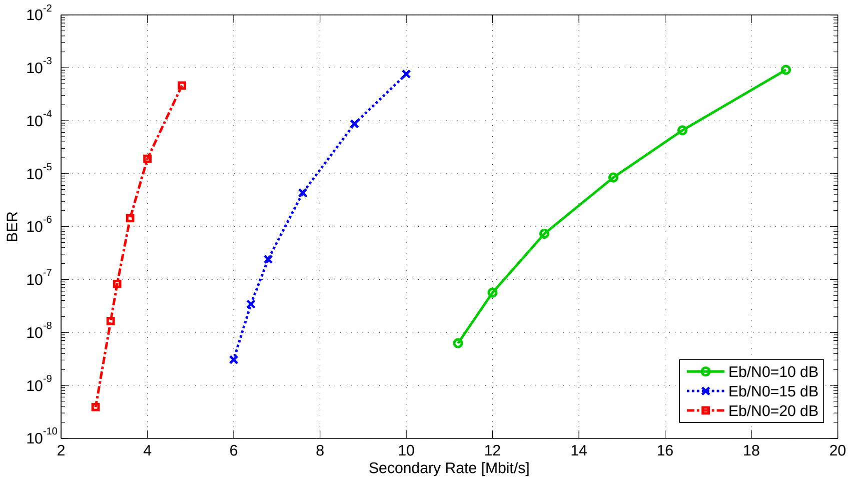

Fig. 9.5 BER vs. *Secondary* Rate: Case B

Radio systems, where low E_b/N_0 values at the *primary* heavily impair the *secondary* achievable performances.

In the second case (Case B), where the two systems are closer, it can be noted that the outcomes are different in comparison with the Case A. In fact, for a fixed BER, the achieved rate increases as the *primary* E_b/N_0 decreases. This is due to the closeness between the two systems. In this case, the interference of the *secondary* system is higher than in the Case A and, therefore, the *secondary* one can use only the carriers that the *primary* system discards because of the fading and these increase as the *primary* E_b/N_0 decreases.

Another interesting element is represented by the modification of the experimented *SINR* at the *primary* and *secondary* receivers before and after *secondary* transmission. Fig. 9.6 reports for the Case A and for each subcarrier, the *primary* (on the left) and *secondary* (on the right) *SINR* before and after *secondary* activation, for a fixed *secondary* BER.

The considered *primary* E_b/N_0 values are 10, 15 and 20 dB, whereas the *secondary* BER is fixed to 10^{-3}. The dashed red line represents the *SINR* before the *secondary* activation. The channel frequency selectivity provides a variable response for both systems. The cognitive process places power where the *secondary* channel is in a good state, and after its activation, the corresponding *primary SINR* lowers (i.e. the interference from the *secondary* increases). As it can be seen, as larger is E_b/N_0, as larger is the number of carriers where the *secondary* is allowed allocating power; this explains the operating point dependence of Fig. 9.4.

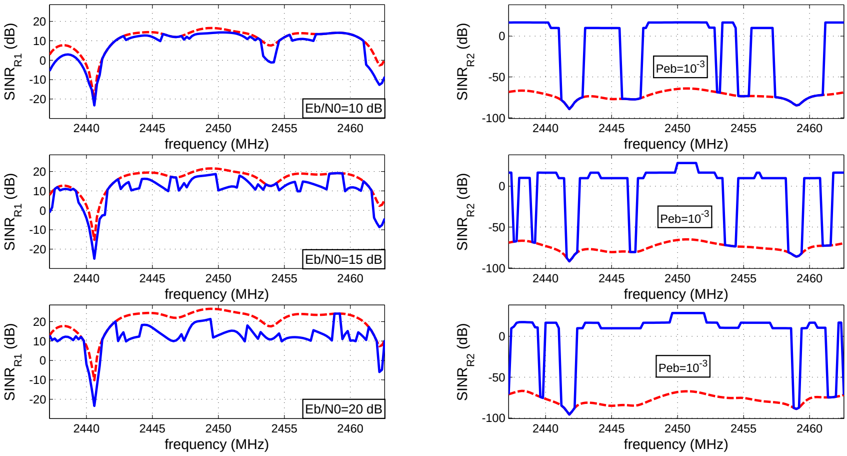

Fig. 9.6 SINR vs frequency for the *primary* (left) and *secondary* (right) systems: Case A

9.3.2 Mixed Satellite/Terrestrial Context

Also for the mixed satellite/terrestrial scenario, the achieved rate of the *secondary* system is considered as the main performance index.

In this case, the six target BER values of the *secondary* system are different with respect to the fully terrestrial scenario and, in particular, they are: $10^{-2}, 5 \cdot 10^{-3}, 10^{-3}$, $5 \cdot 10^{-4}, 10^{-4}, 5 \cdot 10^{-5}$. The three E_b/N_0 values for the *primary* receiver are, instead, the same of the previous scenario: 10 dB, 15 dB and 20 dB.

For this context, two different environments, CITY and HIGHWAY, have been considered. The terminal displacements are shown in Fig. 9.7.

As it can be seen, the distance between the *secondary* terminals, Tx_2 and Rx_2, is fixed and it is set to 50 meters while the receiver of the *primary* system, Rx_1, approaches the *secondary* cluster at different distances. The performance has been evaluated for three distance values among the three terminals: $100-100-50$ meters, $70-70-50$ meters and $50-50-50$ meters.

In Fig. 9.8, for each distance and for each E_b/N_0 value of the *primary* system, it is reported the *secondary* rate value in the CITY environment with the target BER equal to 10^{-2}. It is important to note that as the distances among terminals decrease, the *secondary* rate decreases, as well. As already said, this is due to the increase of the interference between the two systems and to the lower power that the *secondary* can use when it is approaching to the *primary* in order to protect the licensed service.

Another interesting element is to assess the *secondary* rate performance for the two analysed environments. In Fig. 9.9 and Fig. 9.10 which consider the cases of $70-70-50$ and $50-50-50$ distance values, it can be seen that the achieved *secondary* rate is lower in the CITY case. This is due to the presence of a strong shad-

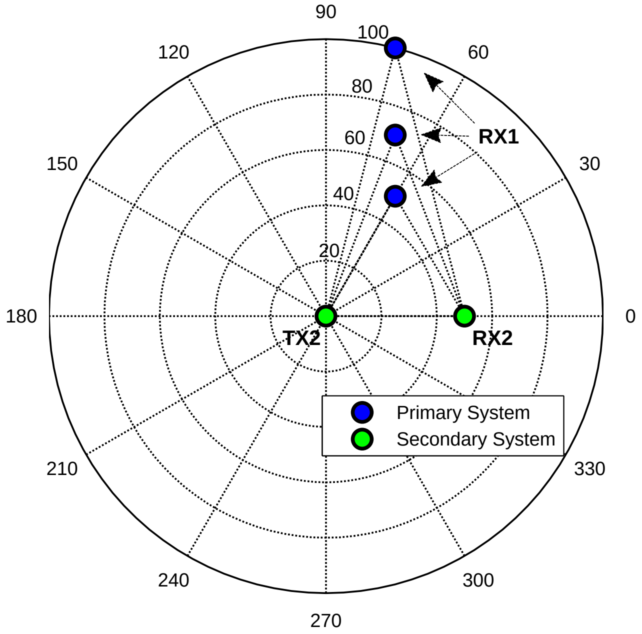

Fig. 9.7 Terminals displacements: polar representation of the different considered distances

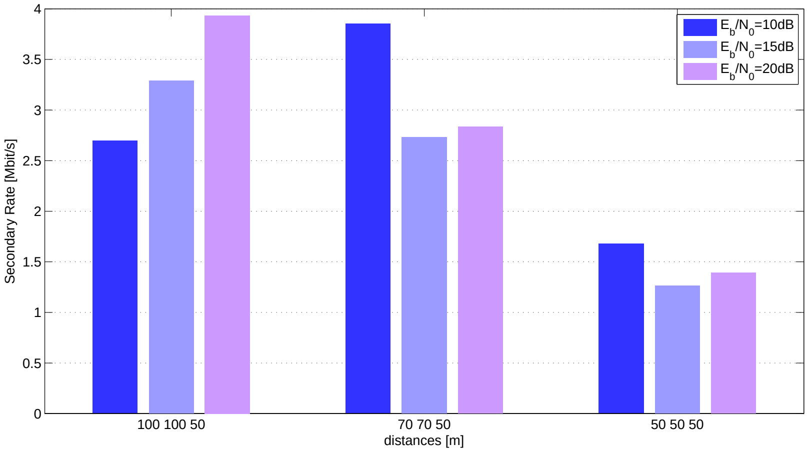

Fig. 9.8 Secondary Rate vs. Distances: HIGHWAY environment, E_b/N_0: 10 dB, 15 dB and 20 dB, *Secondary target BER* $= 10^{-2}$

owing in the CITY environments, resulting in an impaired reception of the *primary* signal. The cognitive strategy has to guarantee the *primary* rate so the *secondary* system has to minimise its transmission.

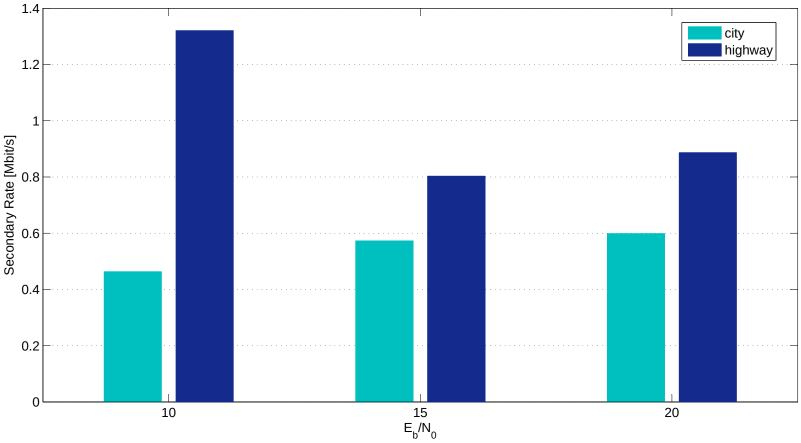

Fig. 9.9 Secondary Rate comparison: HIGHWAY and CITY environments, distance values $50-50-50$, $Secondary\ target\ BER = 10^{-2}$, E_b/N_0: 10 dB, 15 dB and 20 dB

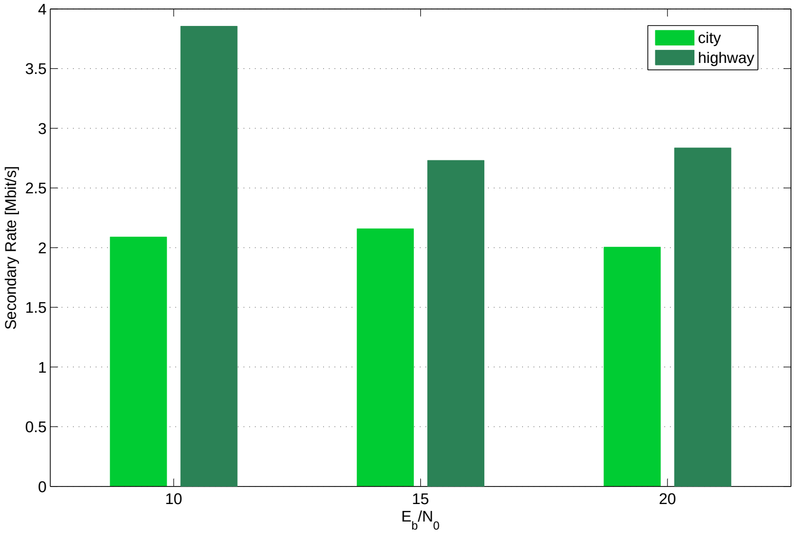

Fig. 9.10 Secondary Rate comparison: HIGHWAY and CITY environments, distance values $70-70-50$, $Secondary\ target\ BER = 10^{-2}$, E_b/N_0: 10 dB, 15 dB and 20 dB

Conclusions

This work has been focused on the investigation of different transmission and reception techniques at Physical and MAC layer which allow improving the performance of satellite users displaced in severe environments and increasing the efficiency in the usage of radio spectrum resources in case satellite and terrestrial systems "coexist" and, therefore, share the spectrum frequencies, in a given area.

The choice to investigate these topics derives from the increasing interest in satellite communications and in their integration with terrestrial wireless communications and from the analysis of critical issues and weaknesses in this research area, such as the use of satellite and terrestrial systems in severe environments (mobile, rural, etc.), in a context where close to an increasing demand of broadband services there is a scarcity of radio resources.

These considerations have motivated the use of adequate advanced techniques to achieve a sufficient quality in satellite links, especially in the more critical uplink, such as *cooperative communications*, and the adoption of strategies based on the *Cognitive Radio* concept able to enable new terminals which do not have license to transmit, to access to licensed band in a transparent way or to occupy available spectrum *holes*.

The adoption of these different techniques and methodologies in various applications scenarios has led to the achievement of interesting results by the point of view of improvement of the system performance in terms of Bit Error Rate, Packet Error Rate and Throughput. More specifically, summarising the outcomes for each considered topic, it can be concluded that:

- The introduction of the *Coded-Cooperation* for DVB-RCS terminals working in a land vehicular scenario, allows improving considerably, for increasing E_b/N_0 values, the system performance compared with the non-cooperative system in both environments that have been analysed (highway and suburban), especially if a codeword partitioning scheme maximising the level of randomness in the distribution of the sub-blocks among different users is adopted. In the best simulated scenario, if it is considered a CER value of 10^{-5}, the system performance is, however, still roughly 3.8 dB away from the reference AWGN+BEC case, leaving significant room for further optimisation of the system. Moreover, a trade-off between the number of cooperative users, the resulting system complexity and the achievable performance is necessary.

- Also the adoption of a *Selective Forwarding* cooperation in a DVB-RCS land-vehicular scenario, allows improving sensibly the system performance in the considered environments, depending on the number of users involved in the cooperation process. The simulation results have shown that, considering 4 cooperators which cooperate with 2 active users, a cooperation gain equal to 1.4 dB in the *ideal* case and equal to 1 dB in the best *real* case, can be achieved with respect to the case of absence of cooperation. Moreover, the theoretical analysis on cooperation has confirmed the results achieved through simulations, proving that the cooperation statistically increases amplitudes values, compared with the no cooperation case, of the random variable which represents the overall fast fading in case of cooperation, moving the Probability Density Function and the Cumulative Density Function curves towards bigger values.
- The assessment of cooperation effects at MAC layer in DVB-RCS systems, through the implementation of a modified resource allocation mechanism, has shown that the achieved results in terms of *aggregated average throughput*, calculated for different source loads, confirm those obtained in terms of Bit Error Rate and Packet Error Rate at Physical Layer: the use of cooperation can allow improving system performance depending on the number of cooperators considered and the different channel conditions which they are subject to. In particular, the advantage of using the cooperation is very remarkable if the throughput curves obtained computing the aggregated throughput averaged over sessions where the channel state is only LOS, Shadowed and Blocked, are considered. Moreover, although transmitting in the whole frame allows tolerating higher source loads and, therefore, achieving higher values of throughput, if the system is sized in order to be far from the region of saturation of the cooperative system, the effect of cooperation is remarkable and the case with 2 cooperators per user achieves the best performance, even using only half frame to transmit informative packets.
- *Cognitive Radio* is one of the most effective solution to the widespread waste of spectrum radio resources due to the poor utilisation of large licensed bands. The proposed heuristic dynamic *Cognitive Radio* strategy for *spectrum sharing*, allows a *secondary* OFDM based system to exploit, under specified conditions, the radio resources (used and unused) of a licensed *primary* system. Achieved performances in terms of rate for the *secondary* system show that, in the considered scenarios, fully terrestrial and mixed satellite/terrestrial, the proposed strategy is able to maximise *secondary* rate by maintaining unchanged the target performances of the corresponding *primary* service.

This research activity has led to the achievement of interesting results. However, a further investigation in this area could be appealing. Among the possible future works, the development of a *joint cooperative-cognitive radio* system could be an interesting research activity to be carried out. In fact, a cooperative transmission among *secondary* users to improve spatial diversity could be realised or also a cooperative transmission between *primary* and *secondary* users could be implemented in order to help *primary* users to finish their transmission quickly for leaving more free *holes* for the *secondary* users. Moreover, cooperative communications could be also used in *spectrum sensing* and in *spectrum sharing*.

Finally, another interesting step could be the adoption of more complex resource allocation schemes both in cooperative and in *Cognitive Radio* systems, based, for example, on Game Theory.

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Appendix A
An Overview on Research Projects Activity

During the three years of Ph.D. Program, the candidate, Rosalba Suffritti, has also contributed to carry out activities related to some research projects concerning different aspects of satellite communications and their integration with terrestrial systems.

In particular, the main performed activity has concerned a three-year national project, called *STEEL* (*Systems, enabling Technologies and mEthods for distance learning*)[1], funded by the Italian Ministry for Education, University and Research in 2007.

This project aims at realising an innovative, efficient and flexible satellite-terrestrial platform integrated with a Learning Management System for distance learning applications, aligned with the latest educational requirements and integrating the most advanced technological solutions suitable for this field, with special attention to Open Source tools. Such a platform considers both synchronous and asynchronous session mode and it is suitable by different kinds of users (mobile, nomadic, residential) and terminal classes (handheld, portable, fixed). Through the STEEL network, in 2010, a series of real distance learning courses will be delivered in order to verify the obtained level of quality as what concerns both technological and educational aspects, in terms of quality of service and perceived quality by end users.

The work carried out by the candidate in this context has concerned both technical aspects (software development, hardware configuration, writing of technical reports, etc.) and management functions.

As for the technical aspects, the research activity related to this work has been focused on the definition of the system architecture and of its main components (satellite and terrestrial). Satellite technology can be particularly important in the e-learning context because it is characterized by several peculiar capabilities such as the opportunity to deliver symmetrical (complete satellite interactivity) and asymmetrical (terrestrial return or broadcast only) services; guaranteed Quality of Service (QoS); rapid deployment; flexibility; easy expansion of the network at regional, national and European level; interoperability with existent terrestrial networks; available bandwidth suited

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[1] STEEL project Web site, http://steel.cilea.it/

for the delivery multimedia contents; multicast capability, etc.

Moreover, in order to provide a guaranteed QoS to the end users, the activities have investigated network solutions which allow achieving scalable services and efficient routing techniques suitable to such a heterogeneous network. Among various well-known QoS approaches, the *Differentiated Services* (Diff-Serv) approach has been taken into account. DiffServ is a coarse-grained, class-based mechanism for traffic management. It relies on a mechanism to classify and mark packets as belonging to a specific class. The Diff-Serv architecture is based on a simple model where traffic entering a network is classified and, possibly, conditioned at the boundaries of the network (INGRESS Node), and assigned to different behavior aggregates. Each behavior aggregate is identified by a single Diff-Serv codepoint. Within the core of the network (Diff-Serv Domain), packets are forwarded towards their destination according to the per-hop behavior associated with the Diff-Serv codepoint. The nodes which handle the traffic in output from the Diff-Serv Domain are called EGRESS Nodes. In the STEEL network, the Diff-Serv Domain is composed by the satellite network in order to guarantee a certain level of QoS, the INGRESS Node is the network node where there are the contents to be distributed and the EGRESS Nodes are, directly, the end users.

Concerning, instead, the advanced routing features, the MPLS (Multi Label Switching Protocol) encapsulation, has been taken into account because it is a highly scalable, protocol agnostic, data-carrying mechanism. The work has also concerned the software and hardware implementation and the testing of INGRESS and EGRESS Nodes, named, in this case, STEEL boxes, which perform the required traffic classification and conditioning through the usage and customisation of Linux packages for the Advanced Routing and Traffic Control. In the STEEL system, MPLS mechanism has been configured to provide a seamless integration with DiffServ techniques on network segments interconnected by satellite links. STEEL boxes act as Label Edge Routers (LER) at the boundaries of the QoS controlled IP network whose inner segments are represented by satellite connections. *Differentiated services over MPLS* are realised by using the label to distinguish between service classes. In this case, the LSP (Label Switched Path) shows the path to the destination, as well as the treatment desired for the packets travelling through that path. The considered queueing discipline is the class-based *qdisc htb* (Hierarchy Token Bucket) because it facilitates guaranteeing bandwidth to classes, while also allowing specification of upper limits to inter-class sharing.

Within the project management activities, instead, the candidate has contributed to the coordination of work activities performed by its own Research Unit and the other Research Units involved in the project, organising also most of project meetings.

Finally, the candidate has worked in the *ESA* project "*Emulator for an ETSI BSM-compliant SI-SAP interface*" started in May 2009, which aims at designing a SI-SAP interface emulator to be integrated into a DVB-RCS/S2 satellite system emulator, in order to assess the advantages offered by such combination and benefits that it can bring to the overall system efficiency. In this regard, the DVB-RCS/S2 enhancements will be developed as an extension to the current DVB-RCS/S2 standard and will be aligned with the SatLabs recommendations. Finally, the support of a satellite terminal manufacturer is exploited to perform the whole work by taking commercial DVB-RCS/S2 systems as reference.

Within the activities of this project, the candidate has dealt with multicast and address resolution issues and she has contributed to the writing of technical reports required in the various tasks of the project.

Publications

During the three years of Ph.D. program, the candidate, Rosalba Suffritti, has published the outcomes of her research activity in international conference proceedings and international journals.
The complete list of publications is the following:

1. S. Morosi, R. Fantacci, E. Del Re, R. Suffritti, *Iterative Demapping and Decoding for DVB-S2 Communications*, 2006 Tyrrhenian International Workshop on Digital Communications, September 2006.
2. S. Morosi, R. Fantacci, E. Del Re, R. Suffritti, *Soft Demapping and Iterative Decoding for Satellite Communications*, IEEE International Communications Conference (ICC) 2007, June 2007.
3. R. Suffritti, E. Del Re, S. Morosi, *Soft Demapping and Iterative Decoding for Satellite Broadcasting Communications*, International Workshop on Satellite and Space Communications (IWSSC) 2007, September 2007.
4. M. Buti, S. Bertorelli, A. Paraboni, L.S. Ronga, R. Suffritti, *Project of a Large Data Collection of Multisite Real Time Attenuations in Ka Band Based on Skyplex Technology*, 13*th Ka* and Broadband Communications Conference, September 2007.
5. E. Del Re , F. Argenti, L.S. Ronga, T. Bianchi, R. Suffritti, *Power Allocation Strategy for Cognitive Radio Terminals*, First IEEE International Workshop on Cognitive Radio and Advanced Spectrum Management (CogART2008), February 2008.
6. R. Suffritti, G. Liva, S. Scalise, L. S. Ronga, S. Morosi, *Performance Assessment of DVB-RCS Coded-Cooperative Terminals for Land-Vehicular Communications*, 14*th Ka* and Broadband Communications Conference, September 2008.
7. E. Del Re, L.S. Ronga, R.Suffritti, *An Integrated Technological Platform for Distance Learning: the STEEL Project*, IADIS International Conference Mobile Learning 2009, February 2009.
8. E. Del Re, G. Gorni, L.S. Ronga, R. Suffritti, *Resource Allocation in Cognitive Radio Networks: a Comparison between Game Theory based and Heuristic Approaches*, Wireless Personal Communications Journal, Vol. 49, No. 3, May 2009.

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13. E. Del Re, L.S. Ronga, R. Suffritti, *Selective forwarding cooperation for DVB-RCS mobile terminals in land-vehicular scenario*, 15*th Ka* and Broadband Communications Conference, September 2009.
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15. E. Del Re, S. Morosi, S. Jayousi, L.S. Ronga, R. Suffritti, *Satellite Role in Emergency Services*, European Wireless Technology Conference, EuWiT 2009, September 2009.
16. E. Del Re, M. Delfino, G. Limongiello, D. Persico, I. Scancarello, R. Suffritti, *Systems, enabling technologies and methods for distance learning: the STEEL project*, to appear in ISDM (Information Sciences for Decision Making) journal by December 2009.
17. E. Del Re, M. Delfino, G. Limongiello, D. Persico, I. Scancarello, R. Suffritti, *Sistemi, Tecnologie Abilitanti e Metodi per la formazione a distanza: il Progetto STEEL*, to appear as a chapter of the book: M. Pieri, D. Diamantini (Eds), *Ubiquitous learning*, Milano: Guerini e Associati, to be published by January 2010.