Thesis for the degree of Doctor of Philosophy

High Performance Signal Processing-Based Collision Resolution for Random Access Schemes

Oscar del Río Herrero

laSalle
Universitat Ramon Llull

Enginyeria i Arquitectura La Salle
Universitat Ramon Llull

Barcelona 2015

High Performance Signal Processing-Based Collision Resolution for Random Access Schemes

Oscar del Río Herrero
European Space Agency
The Netherlands
E-mail: oscar.del.rio.herrero@esa.int

Advisor: Dr. Joan Lluís Pijoan Vidal
Enginyeria i Arquitectura La Salle, Universitat Ramon Llull, Barcelona, Spain.

This thesis has been prepared using LaTeX.

Abstract

Over the past years there has been a fast growing demand for low-cost interactive satellite terminals supporting both fixed and mobile services, such as consumer broadband access, machine-to-machine communications (M2M), supervisory control and data acquisition (SCADA), transaction and safety of life applications. These networks are generally characterized by a large population of terminals sharing the available resources under very dynamic traffic conditions. In particular, in the return link (user to network) of commercial satellite broadband access networks, residential users are likely to generate a large amount of low duty cycle bursty traffic with extended inactivity periods. A similar situation occurs in satellite mobile networks whereby a large number of terminals typically generate infrequent packets for signalling transmission as well for position reporting or other messaging applications.

These services call for the development of efficient multiple access protocols able to cope with the above operating conditions. Random Access (RA) techniques are by nature, good candidates for the less predictive, low duty cycle as well as time sensitive return link traffic. Besides, RA techniques are capable of supporting large population of terminals sharing the same capacity and require low terminal complexity. RA schemes have been widely studied and deployed in terrestrial networks, but do not perform well in the satellite environment, which is characterized by very long propagation delays. Today, their use in satellite networks is mainly limited to initial network login, the transmission of control packets, and in some cases, for the transmission of very small volumes of data with very low channel utilization.

This thesis proposes three novel RA schemes well suited for the provision of the above-mentioned services over a satellite environment with high performance and low terminal complexity. The new RA schemes are Contention Resolution Diversity Slotted Aloha (CRDSA), Asynchronous Contention Resolution Diversity Aloha (ACRDA) and Enhanced Spread Spectrum Aloha (E-SSA), suited for slotted, unslotted and spread spectrum-based systems respectively. They all use strong Forward Error Correction (FEC) codes, able to cope with heavy co-channel interference typically present in RA, and successive interference cancellation implemented over the successfully decoded packets. The new schemes achieve a normalized throughput above 1 bit/s/Hz for a packet loss ratio below 10^{-3} which represents a 1000-fold increase compared to Slotted ALOHA. The performance of the proposed RA schemes has been analyzed by means of detailed simulations as well as novel analytical frameworks that characterize traffic

and packets power statistical distributions, the performance of the FEC coding as well as the iterative interference cancellation processing at the receiver.

Keywords: Access control, interference suppression, multiaccess communication, satellite communication, time division multiple access, code division multiaccess, satellite mobile communication, SCADA systems.

Acknowledgements

First of all, I would like to thank my Ph.D. Thesis advisor, Dr. Joan Lluís Pijoan from Escola Universitària d'Enginyeria i Arquitectura La Salle in Barcelona (Spain) for his highly valuable inputs, his academic guidance and for helping me in organizing my research into the form of a thesis.

Special thanks to Dr. Riccardo De Gaudenzi, from the European Space Agency in The Netherlands, for his continuous guidance and advice, and for getting as motivated as me in this fascinating field of research.

I would also like to thank Enrico Casini and Guray Acar from the European Space Agency in the Netherlands, Gennaro Gallinaro from Space Engineering in Italy, Jean Pierre Choffray from SES-ASTRA in Luxembourg, Daniel Delaruelle from Newtec in Belgium, Antonio Arcidiacono and Daniele Finocchiaro from Eutelsat in France, Pål Orten and Alv Aarskog from Thrane & Thrane in Norway (formerly Nera SatCom). They have all provided highly experienced inputs to the novel random access schemes proposed in this thesis.

Norman Abramson from Aloha Networks, with an extensive research in ALOHA based RA schemes, has served as a very important source of inspiration for my PhD.

I wish to thank my wife Marta for her strong support and encouragement over the years during which I have studied, my children Claudia and Gabriel for their patience and understanding and my parents for their continuous moral support.

This thesis would have not been possible without the support of the European Space Agency, which allowed me to engage myself for many years in this field of research.

Finally, I would like to thank Escola Universitària d'Enginyeria i Arquitectura La Salle in Barcelona (Spain) for their kindness and enthusiastic support given to me during all the years I have studied at the University.

About the author

Oscar del Rio Herrero was born in Barcelona, Spain, in 1971. He received the B.E. degree in Telecommunications and the M.E. degree in Electronics from Universitat Ramon Llull, Barcelona, Spain, in 1992 and 1994, respectively. He received a post-graduate degree in Space Science and Technology with emphasis in Satellite Communications from the Space Studies Institute of Catalonia (IEEC), Barcelona, Spain, in 1995. He joined ESAs Research and Technology Centre (ESTEC), Noordwijk, The Netherlands, in 1996. In 1996 and 1997 he worked as a Radio-navigation System Engineer in the preparation of the Galileo programme. From 1998 to 2009, he has worked as a Telecommunications Systems Engineer in the Communication - TT&C systems and techniques section. Since 2010 he is working for the Iris programme in the ESA's Telecommunication Directorate, aiming at the development of a new satellite-based Air-Ground Communication system for Air Traffic Management.

In autumn 1994 he started a doctoral programme on *Information and Communications Technologies and Their Management* at Escola Universitària d'Enginyeria i Arquitectura La Salle, Universitat Ramon Llull, in Barcelona (Spain). During the period 1994 to 1998, he completed his post-graduate Ph.D. courses and initiated himself in the research world. In 2007 he presented his thesis for Diploma d'Estudis Avançats (DEA) with title *Signal Processing Based Collision Resolution in Random Access Schemes for Large Satellite Networks*. During the period 2001-2014 he has focused his research primarily to multiple access and radio resource management in satellite networks.

Research Environment

The European Space Agency (ESA) and its 20 Member States work together to pursue a wide range of ambitious and exciting goals in space. Together, they create fascinating projects that would not be feasible for the individual Member States. These projects generate new scientific knowledge and new practical applications in space exploration, and contribute to a vigorous European aerospace industry.

ESA has sites in several European countries. The European Space Research and Technology Centre (ESTEC), the largest site and the technical heart of ESA - the incubator of the European space effort - is in Noordwijk, The Netherlands. Most ESA projects are born here, and this is where they are guided through the various phases of development. More than 2000 specialists work here on dozens of space projects. Except for launchers, nearly all ESA projects are managed from ESTEC. In Noordwijk, people work on science missions, on human spaceflight, telecom, satellite navigation, and Earth observation. ESTEC also houses a large pool of people with highly specialized technical knowledge, who are assigned to space projects when their expertise is needed for missions.

The Communication - TT&C systems and techniques section is part of the RF Payload Systems division. The group, of about 20 people, is composed of staff, contractors, research fellows, Ph.D. students, graduate trainees and stagiaires. The areas of expertise of the section are:

- Telecommunications (physical and medium access control layer techniques, system architectures, advanced digital modems);
- Telemetry, tracking and command systems and techniques for spacecrafts targeting deep space, Earth exploration, space operations and telecommunication;
- Security of TT&C links and Telecom communications.

The main roles of the section are to provide support to a wide range of ESA programmes (Telecommunications, Navigation, Deep Space exploration, Earth Observation, Security), ensure the implementation and development of advanced technologies, actively contribute to the development of telecommunication standards in cooperation with European industries and international standardization bodies, provide consultancies to external customers (e.g. EC, SES-ASTRA, Eutelsat, Inmarsat and others) and perform internal research. The section has performed pioneering work in satellite on-board processing for both regenerative and bent-pipe satellites, advanced CDMA VSAT and mobile networks, multiuser detection and random access for consumer broadband and mobile networks, high-speed modems for high spectral and power efficient modulations, application of adaptive coding and modulation to Ka-band, satellite UMTS pilot systems and system analysis tools.

Summary of contributions

This thesis is the result of the research carried out in the following contributions:

- Slotted Random Access
  - E. Casini, R. De Gaudenzi, O. del Río Herrero, *Contention Resolution Diversity Slotted Aloha (CRDSA): an Enhanced Random Access Scheme for Satellite Access Packet Networks*, IEEE Transactions on Wireless Communications, Vol. 6, Issue 4, pp. 1408-1419, April 2007
  - O. del Río Herrero, R. De Gaudenzi, *Generalized Analytical Framework for the Performance Assessment of Slotted Random Access Protocols*, IEEE Transactions on Wireless Communications, Vol. 13, Issue 2, pp. 809-821, February 2014

  - E. Casini, O. del Río Herrero, R. De Gaudenzi, M. E. Delaruelle, J.P. Choffray, *Transmission de donnees par paquets a travers un canal de transmission partage par plusierus utilisateurs*, European Patent EP1686746, 30 January 2006

- Unslotted Random Access
  - O. del Río Herrero, R. De Gaudenzi, *High Efficiency Satellite Multiple Access Scheme for Machine-to-Machine Communications*, IEEE Transactions on Aerospace and Electronic Systems, Vol. 48, Issue 4, pp. 2961-2989, October 2012
  - O. del Río Herrero, R. De Gaudenzi, *Methods, apparatuses and system for asynchronous spread-spectrum communication*, European Patent EP2159926, 26 August 2008
  - R. De Gaudenzi, O. del Río Herrero, G. Acar, E. Garrido Barrabés, *Asynchronous Contention Resolution Diversity Aloha: Making CRDSA Truly Asynchronous*, IEEE Transactions on Wireless Communications, Vol. 13, Issue 11, pp. 6193-6206, November 2014
  - R. De Gaudenzi, O. del Río Herrero, *Method and apparatus for transmitting data packets over a transmission channel shared by a plurality of users*, World Intellectual Property Organization Patent WO/2015/000518, 3 July 2013

In addition, the following papers from the author provide complementary information and analyses to the main area of research of the present thesis:

- O. del Río Herrero, R. De Gaudenzi, J. Pijoan Vidal, *Design Guidelines for Advanced Random Access Protocols*, 30st AIAA International Communications Satellite Systems Conference (ICSSC), 24-27 Sep. 2012, Ottawa (Canada)

- O. del Río Herrero, R. De Gaudenzi, *A High-Performance MAC Protocol for Consumer Broadband Satellite Systems*, 27th AIAA International Communications Satellite Systems Conference (ICSSC), 1-4 Jun. 2009, Edinburgh (UK)

- E. Casini, R. De Gaudenzi, O. del Río Herrero *Contention Resolution Diversity Slotted Aloha Plus Demand Assignment (CRDSA-DA): an Enhanced MAC Protocol for Satellite Access Packet Networks*, 23rd AIAA International Communications Satellite Systems Conference, 25-28 Sep. 2005, Rome (Italy)

- O. del Río Herrero, G. Foti, G. Gallinaro, *Spread-Spectrum Techniques for the Provision of Packet Access on the Reverse Link of Next-Generation Broadband Multimedia Satellite Systems*, IEEE Journal on Selected Areas in Communications, Vol. 22, Issue 3, pp. 574-583, April 2004

The following publications provide a summary of the new random access schemes proposed by the author:

- O. del Río Herrero, R. De Gaudenzi, G. Gallinaro, *High-performance random access schemes*, in Co-operative and cognitive satellite systems, S. Chatzinotas, B. Ottersten, R. De Gaudenzi, Ed. Academic Press, 2015, pp. 35-82

- R. De Gaudenzi, O. del Río Herrero, *Advances in Random Access Protocols for Satellite Networks*, 2009 International Workshop on Satellite and Space Communications (IWSSC 2009), 10-11 September 2009, Siena (Italy)

Contents

Part I

Overview

Chapter 1

Motivation and goals

This chapter provides a historical review of satellite communications, in particular from the perspective of the multiple access protocols. From this review, the motivation and goals for the present PhD thesis are derived.

1.1 Motivation

1.1.1 A brief history of satellite communications and services

The Space Race (1955-1972) between the Soviet Union (USRR) and the United States (US) opened up the era of satellite communications. In 1957, the Soviet Union launched the first communications satellite (Sputnik 1) into an elliptical Low Earth Orbit (LEO). It was a 58 cm diameter polished metal sphere, with four external radio antennas to broadcast radio pulses. In 1958 the US launched the first satellite which broadcast a recorded Christmas greeting from President Eisenhower during 13 days (Project SCORE). In 1960 the US launched the first active repeater communications satellite (Courier 1B) and was also the first communications satellite powered by solar cells to recharge storage batteries [1]. In 1962 the US launched Telstar 1 and Relay 1 wideband (microwaves) repeater satellites on elliptical LEO orbits, which relayed the first live television signals across the atlantic and pacific oceans respectively. Syncom 3 was the first geostationary (GEO) communication satellite, launched on 1964, and was used to broadcast the 1964 Summer Olympics in Tokyo to the United States. The first commercial geosynchronous satellite, Intelsat I, was launched in 1965, as well as, the first Soviet communication satellite on an inclined Highly Elliptical Orbit (HEO), Molniya 1. Such orbits allowed the satellites to remain visible to sites in polar regions for extended periods, unlike geostationary satellites which appear below the horizon at very high latitudes. In 1974, NASA launched the ATS-6 satellite, which was a precursor to many technologies still in use today on geostationary spacecraft: large deployable antenna (9 m), direct to home (DTH) broadcasting, 3-axis stabilized and antenna pointing through RF sensing. The first in a series of Soviet GEO satellites to carry DTH television was launched on 26 October 1976 (Ekran 1). They were both using ultra-high frequency (UHF) band (around 700-800 MHz), so that the transmissions could be received with existing UHF television technology. Due to the limited performance of the first satellites, initial systems had low capacity, required expensive large earth stations with antennae of 15 to 30 m diameter and were used to gather the traffic from an extensive area by means of a ground network and to relay the signals across the oceans (point-to-point trunk connections).

During the 1980s and the 1990s, the development of satellite microwave (GHz) technologies, such as contoured multi-beam antennae with higher gain and high power transmission amplifiers (200-300W), enabled the use of smaller earth stations affordable to the end user. These smaller earth stations, typically have a satellite dish antenna ranging from 0.6 to 3.5 m diameter and can be receive-only DTH terminals or bidirectional Very Small Aperture Terminals (VSAT). Their smaller size also enabled mobile services (e.g. on vessels, trains, airplanes). Initial VSAT terminals supported download speeds ranging from few hundred kbps to tens of Mbps and upload speeds ranging from few kbps to few Mbps. The reduced size of satellite terminals resulted in a rapid increase in the number of VSAT networks (including networks with several hundreds of sites), and the emergence of new narrowband and broadband satellite communications services exploiting the satellite's natural capability to collect or broadcast signals from or to several locations over a very large coverage area: corporate networks, multi-point data transmission networks (retail point-of-sale or automatic teller machine transactions), data collection networks (polling RFID tags, supervisory controlled and data acquisition - SCADA), satellite news gathering, satellite broadcast networks (to cable heads or directly to the consumer) [2]. These satellites where typically operating in the C-band (4-8 GHz) and Ku-band (12-18 GHz).

Nowadays, most communications GEO satellites carry dozens of transponders, each with a bandwidth of tens of megahertz, providing a very high capacity at a reduced communications cost. Communications satellites have a typical launch mass between 3000 and 6000 kg, a payload DC power between 5 kW and 20 kW and a design lifetime of 15 years. Most transponders operate like a "bent pipe", relaying back to earth the received signals after performing amplification and a shift from uplink to downlink frequency. High Throughput Satellites (HTS), such as Anik F2 (2004), Thaicom 4 (2005), Spaceway 3 (2007), KA-SAT (2010), ViaSat-1 (2011), Yahsat Y1B (2012), EchoStar XVII (2012), Inmarsat Global Xpress (2013, 2015, 2016) and Intelsat EpicNG (2016), offer capacities around 100 Gbps which significantly reduces the cost per bit. The majority of HTS operate in Ka-band (20-30 GHz), and the massive increase in capacity is achieved by employing frequency re-use across multiple narrow spot beams (usually in the order of 100s of kilometers per spot beam) [3]. ViaSat -1 satellite has 72 spot beams, KA-SAT has 82, EchoStar XVII has 60 and Inmarsat 5 has 89 spot beams. These satellites support two-way communications at higher speeds (e.g. 50 Mbps download and 10 Mbps upload) with small satellite dish antennae (60-70 cm). Typical services offered are broadband connectivity to the consumer and professional markets both fixed and mobile (e.g. land mobile, maritime, aeronautical). The Alphasat communications satellite (2013) is another example of a large spacecraft, operating in L-band (1-2 GHz) with a launch mass of 6650 kg, a payload DC power of 12 kW and a a 12-meter aperture antenna reflector. L-band satellites are well suited for mobile satellite services requiring low data rates, low cost and small size terminals (e.g. handheld, machine to machine communications).

Today, we have around 600 operating communications satellites in orbit, with orders for 20-25 new commercial GEO satellites each year [4]. In 2013 there were about 200 million satellite TV subscribers worldwide (DTH service). These are served primarily via C-band and Ku-band broadcast satellites. Today they are offering Standard Definition (SD) and High Definition (HD) TV. In the near future they will also serve Ultra HD TV and interactive TV services. Satellite TV services account for 78% of all satellite services revenues. Regarding the consumer broadband access, there were 2.5 million subscribers (mostly in North America) in 2014 and is expected to grow worldwide to 8.8 million subscribers in 2023, according to Euroconsult forecasts [5]. Enterprise data services are also gradually migrating from broadcast to HTS satellites due to the lower cost per bit, in particular VSAT networks and cellular (3G and 4G) backhaul. Furthermore, it is also foreseen that HTS will also see capacity demands coming for commercial mobility (e.g. commercial ships, business jets, commercial airlines). Analysts from Northern Sky Research (NSR) forecast that High Throughput Satellites capacity will increase from 500 Gbps in 2013 to 2 Tbps in 2023 [6]. Another market with a strong growth via satellite are Machine-to-Machine (M2M) communications (e.g. remote control and monitoring in transportation and cargo, oil and gas, utilities, military, civil government markets) [7]. Key strengths for M2M via satellite are their reliable connectivity in remote and underserved regions, their global coverage and their independence from terrestrial networks for mission critical applications. The total market forecast by NSR in 2023 for satellite M2M services is $ 2.5 billion with 6 million terminals sold. Majority of the market will be served in L-band, being particularly well suited for this type of services with lower cost and smaller physical size terminals.

1.1.2 The multiple access problem

In the early years of satellite communications, the services provided were telephone and television signals transmission between continents (point-to-point trunk connections). The transmitted signals where analog and each carrier conveyed either a single TV signal or frequency division multiplexed telephone channels [8]. Multiple access to the satellite was done by fixed Frequency Division Multiple Access (FDMA) assignments to each earth station.

For Direct To Home (DTH) television, receive-only terminals are used. The television signals transmitted by the broadcast centre (point-to-multipoint) were initially analog using the NTSC, PAL or SECAM standards and Frequency Modulation (FM). Then, in the mid-1990s digital television standards where adopted exploiting the flexibility to multiplex several TV channels in one carrier and a reduced bandwidth occupation [9], [78]. The digital television signals are transmitted by the broadcast centre using a time division multiplex/phase shift keying modulation (TDM/PSK).

VSAT networks use bidirectional communications and typically have a star topology where VSATs communicate to a larger master earth station (called hub), but may also communicate directly to other VSATs when in mesh configuration [11]. The transmitted signals are digital using a PSK modulation. The use of digital transmission offers a greater flexibility to multiplex different types of services (television, voice, data) over the same satellite channel. Digital transmission also allows an easier interworking with the digital terrestrial networks. A single outbound carrier provides data transfer from the hub to the remote terminals using a TDM/PSK waveform as for DTH television. The inbound channel (multipoint-to-point) typically consists of several lower bit rate carriers operating in Multi-Frequency Time Division Multiple Access (MF-TDMA).

The arrival of the VSAT networks, triggered the need for new multiple access protocols able to efficiently share the satellite communication resources among all VSAT terminals while maintaining acceptable throughout, loss and delay performance. Multiple access is one of the most critical elements to the performance of VSAT networks. Their design is often constrained by their operational environment. The satellite environment is characterized by radio link impairments and a large propagation delay, amongst other inherent attributes (e.g. non-linearities). Typical radio link impairments in the satellite channel are fading and multipath interference. The large propagation delay, in the range of 250 ms for a geostationary satellite, represents a very particular property of the satellite environment that will condition the applicability of terrestrial multiple access schemes over the satellite environment. In the satellite channel, the propagation delay is much larger than the time taken to transmit a packet, and a sender may have sent several packets before the receiver starts receiving the first packet. Satellite multiple access schemes must be able to deal with all these characteristics.

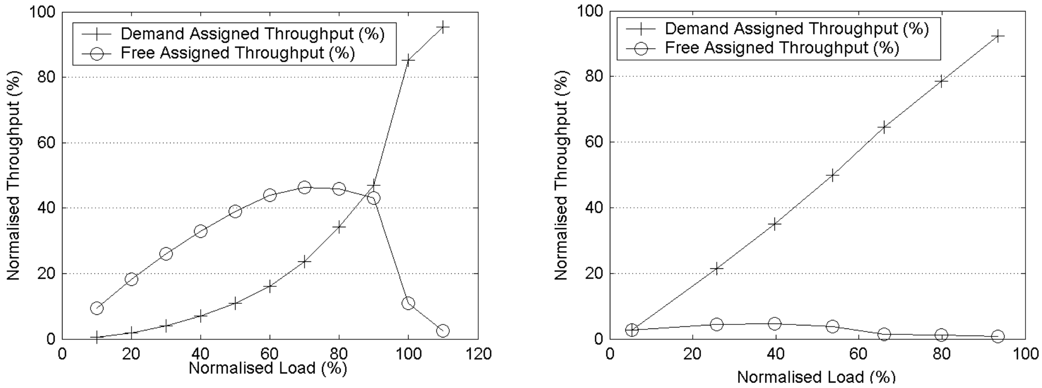
During the 1980's and 1990's numerous multiple access protocols were developed [12, 13, 14, 15, 16, 17, 18, 19]. The available inbound bandwidth resources are divided using FDMA, TDMA, MF-TDMA or Code Division Multiple Access (CDMA) [8]. But as opposed to the fixed assignment multiple access techniques, the new proposed protocols combined demand assignment, random access and fixed assignment to dynamically control the access to the shared resources by the many contending users. These protocols typically have a centralized control (e.g. in the hub) which is managing the access to the satellite resources, as it allows a more efficient multiplexing of services with different priorities (e.g. data, voice, video).

First, with the telephone service a portion of the satellite resources (e.g. frequency channel in FDMA or timeslots in TDMA) were assigned dynamically on a call basis [20] and the grade of service was determined through the the well-known blocking formulas, such as the Poisson and Erlang B formulas used for terrestrial links [21]. But with the increase of data services (e.g. corporate networks interconnection, retail point-of-sale transactions, SCADA), it was necessary to assign satellite resources in a more dynamic way, i.e. on a packet basis rather than call (or circuit) basis. Demand assignment multiple access (DAMA) schemes evolved to introduce faster capacity reservation mechanisms in order to reduce end-to-end transmission times. In the CPODA protocol [24] capacity reservations can be implemented via contention mini slots and piggybacking them in the header of the scheduled packet transmissions. The CFDAMA-PB protocol [25] behaves like the CPODA protocol, but in addition it randomly assigns the unused traffic slots to inactive users. At low traffic loads the chance that an earth station obtains free-assigned slots is high, thus reducing it's end-to-end transmission time to a minimum of one satellite hop propagation delay (i.e. 250 ms for GEO satellites). At high loads, the end-to-end transmission delay is not reduced as no spare satellite resources are left, but the system remains stable

However, the performance of DAMA protocols is highly dependent on the traffic characteristics and the number of earth stations sharing the satellite resources. Internet data traffic is known to be statistically self-similar [22, 23]. Satellite terminals generate heavy tailed bursts of packets with a large variance in the inter-arrival times between bursts. Besides, by aggregating streams of such traffic from different earth stations we intensify the self-similarity (burstiness) instead of smoothing it (fractal-like behavior). In [26] the performance of the CFDAMA-PB protocol has been analyzed with traffic following a Poisson regime, which is more appropriate for voice, facsimile or SCADA type of services, but not for Internet data traffic as described above. In [27], the author studies the sensitivity of the CFDAMA-PB protocol under different types of Internet data traffic and a large number of earth stations (e.g. larger than the number of traffic slots in one satellite hop propagation delay). It is shown that under bursty traffic and a large number of earth stations the performance of CFDAMA-PB is equivalent to a pure DAMA scheme, i.e. the majority of the free capacity assignments are wasted. Figure 1.1 shows that the throughput component for Free-Assigned slots with bursty traffic is very low at all loads, while for Poisson traffic is quite high at loads up to 80%. Under these conditions, every packet transmission undergoes first a reservation cycle (two satellite hops) and then another satellite hop for the packet transmission (i.e. ≥ 750 ms for a GEO scenario) like in a pure DAMA scheme. This poses some limitations on the use of DAMA for consumer broadband access to support real-time or interactive type of applications.

To enhance the performance of DAMA protocols for broadband satellite networks, predictive DAMA protocols have been developed, such as PRDAMA [28]. PRDAMA estimates the positive varying trend of the traffic on each earth station to allocate the free capacity assignments. Non-linear prediction methods are used to predict the traffic burstiness [29]. This results in a more efficient assignment of the free bandwidth to those terminals that are predicted to need the resource, thus minimizing the wastage of free bandwidth assignments. However, the effectiveness of the predictive methods cannot be guaranteed for all traffic data [29]. Besides, the improvement in the end-to-end delay with respect to CFDAMA-PB is rather limited (i.e. ~ 100 ms delay reduction) with an average end-to-end delay over a bent pipe GEO satellite in the order of 750 ms.

In [30] and [31] two combined random/reservation multiple access schemes



(a) Poisson traffic

(b) Bursty traffic

Figure 1.1: CFDAMA-PB throughput decomposition in Demand and Free Assigned slots

have been proposed dubbed CRRMA and RAN respectively. The basic principle is to perform the first transmission attempt in a random access (RA) slot, thus avoiding the initial two hops satellite delay for capacity reservation, and in case it is unsuccessful (i.e. due to collision), perform a second transmission in a reserved slot. RA performs well in front of bursty traffic, but the improvement in delay of the CRRMA and RAN schemes is limited to low loads, due to the high probability of packet collisions at high loads. Packet collisions are destructive in the considered RA scheme (Slotted Aloha). A review of terrestrial RA techniques and their performance over the satellite environment will be the subject of the next section.

A final consideration for DAMA schemes is related to the overheads. All DAMA schemes introduce control subframes that are needed by earth stations to make capacity requests and remain synchronized to the satellite network (e.g. for TDMA). This represents an overhead in the inbound channel which can be very large (i.e. comparable to the data subframes) in networks having a very large number of low duty cycle earth stations (e.g. data collection networks with thousands of earth stations such as for SCADA, M2M). In those networks, RA schemes are typically used.

The arrival of broadband access and M2M communications has triggered the need for further performance improvements of satellite multiple access protocols. The new multiple access protocols shall provide fast access to a very large population of earth stations (tens of thousands) generating bursty traffic with a low duty cycle, while maintaining acceptable throughout, loss and delay performance. RA protocols represent a good candidate solution, as they are insensitive to the network population size and traffic characteristics, provide low access delays and low complexity on the earth stations. RA protocols used in combination with DAMA are also a good alternative to the free capacity assignment scheme for the less predictive, low duty cycle as well as time sensitive traffic in broadband access networks.

1.1.3 Key terrestrial random access techniques and their applicability to satellite

RA protocols originated in the 1970s from the need for terminal-computer and computer-computer communication. In computer communication, data traffic is bursty. Traffic burstiness is the result of the high degree of randomness seen in the message generation time and size, and of the relatively low-delay constraint required by the user. Users generate traffic with a low duty cycle, but when they do, they require a fast response. As a result, there is a large peak-to-average ratio in the required data transmission rate. In this context, it is not efficient to use fixed channel allocation schemes, as they would result in a low channel utilization. A more advantageous approach is to provide a single shared high-speed channel to the large number of users. However, when dealing with shared media conflicts arise when more than one user want to access the shared resources simultaneously. Therefore, the challenge with shared media is to control the access to the common channel while providing a good level of performance and maintaining a reduced implementation complexity. RA protocols where developed to address this multiple access scenario, and today are extensively used in terrestrial networks over wired and wireless shared media [14, 32, 33]. In this section, we review the key terrestrial RA techniques and analyze their applicability to the satellite environment.

One of the most widely used distributed packet access schemes is the Carrier Sense Multiple Access (CSMA) and its variants. In CSMA, a station senses the medium before transmitting and defers to any ongoing transmission [34]. CSMA/ Collision Detection (CSMA/CD) operates similarly to CSMA, but once the transmission has started, if the sender detects a collision it stops transmitting to reduce the overhead of a collision. When collisions occur, each station willing to transmit backs off for a random time period [35]. Collision detection cannot be implemented over a terrestrial wireless network due to the hidden terminal problem where some stations are out of the transmission and detection range of each other [36]. However it performs well in wired networks and the IEEE has standardized CSMA/CD in the IEEE 802.3 standard [37]. Another variant used in wireless networks is to avoid the collisions similarly to the CSMA/Collision Avoidance (CSMA/CA) scheme. In this scheme the sender tries to avoid a collision after the channel becomes idle, by waiting for an Inter Frame Spacing (IFS) time before contending for the channel. The IEEE has standardized CSMA/CA in the IEEE 802.11 standard [38]. The back-off algorithm in CSMA/CA tries to avoid collisions, but does not remove them all. Small values of the random back-off time cause many collisions while very large values can cause unnecessarily long delays. Secondly, CSMA/CA has failed to solve the hidden terminal problem, and cannot always detect that the medium is busy, thus creating a collision in the channel. All the previous multiple access protocols employ carrier sensing to avoid collisions and offer a good channel utilization, low latency and good stability over channels where packet transmission times are larger than propagation delays, but unfortunately cannot operate over satellite channels where propagation delays are very large.

Another type of schemes are distributed reservation schemes, also adopted in terrestrial wireless networks. Reservations can be made either through a hand-shaking on the same channel, or through an out-of-band signaling. There is a large variety of hand-shaking protocols. The simplest one is the Multiple Access Collision Avoidance (MACA) [39] protocol, in which a sender transmits a Request to send (RTS) message to its intended receiver before the data transmission. The data is transmitted only after reception of a Clear To Send (CTS) message from the receiver, which the receiver sends on reception of a successful RTS. The MACAW protocol [40] is an extension of the MACA protocol that introduces enhancements to the RTS-CTS handshaking by adding a Data Sending (DS) frame by the sender prior to data transmission and an Acknowledgement frame (ACK) by the receiver following the data transmission with the aim of solving the hidden terminal problem. The Floor Acquisition Multiple Access (FAMA) [41] protocol combines carrier sensing with RTS-CTS handshaking, again with the aim of solving the hidden terminal problem.

An example of out-of-band signaling protocol is the Busy Tone Multiple Access (BTMA) [36]. In this scheme, a station that is within range and in line-of-sight of all terminals, transmits a busy tone signal on a dedicated busy tone channel, as long as it senses a carrier on the incoming message channel. It is by sensing the busy tone channel that terminals determine the state of the message channel. This scheme solves the hidden terminal problem, but introduces the constraint that a control station needs to be within range of all terminals in the network. Another type of out-band signaling distributed reservation scheme is the Random Access Channel (RACH) used in the third generation (3G) cellular networks [42], where terminals randomly transmit first short packet preambles, and wait for a positive acquisition indicator from the base station prior to the transmission of the complete message (i.e. after successful reservation of the channel). Distributed reservation schemes reduce or eliminate the hidden terminal problem typically present in terrestrial radio links, but also rely on short propagation delays, i.e. the reservation delay only represents a small overhead of the total packet transmission time. In the satellite environment, centralized reservation schemes are used instead [25] to avoid several failed attempts prior to the packet transmission, which could represent a very large overhead to the total end-to-end packet transmission delay.

The pure ALOHA protocol, first proposed by N. Abramson in [43], is one of the oldest and simplest multiple access protocols. In ALOHA, a terminal transmits a packet without checking if any other terminal is active. Within an appropriate timeout period, it receives and acknowledgment from the destination, knowing that no conflict has occurred. Otherwise, it assumes that a collision has occurred and must retransmit. To avoid continuously repeated collisions, the retransmission time is randomized across the terminals, thus spreading the retry packets over time. A slotted version, referred to as Slotted Aloha (S-ALOHA) is obtained by dividing time into slots of duration equal to the duration of a fixed-length packet [44]. Users are required to synchronize the start of transmission of their packets to the slot boundaries. When two packets collide they will overlap completely rather than partially, providing an increase on channel efficiency over pure Aloha. The S-ALOHA has the advantage of higher efficiency, but requires time slot synchronization.

Both schemes are applicable to the satellite environment, as they have no dependency on the propagation delay. Unfortunately, these schemes are subject to a high collision probability (i.e. no carrier sensing), and their operation in the high load region is not practical in the satellite environment due to the high number of retransmissions required yielding very high latencies. The Diversity Slotted Aloha (DSA) [46] is slightly improving the S-ALOHA performance at low channel loads by sending twice the same packet at random locations in order to increase the time diversity and thus reducing the Packet Loss Ratio (PLR). As for S-ALOHA, operation in the high packet collision probability region is not practical in a satellite environment.

It is generally assumed that whenever two packet transmissions overlap in time, these packets destroy each other. This assumption is pessimistic as it neglects capture or near-far effects in radio channels. Capture occurs when a station receives messages simultaneously from two stations, but the signal from one of them drowns out the other, so that no collision occurs. The station with the higher received power is said to have captured the receiver. Some of these effects have been addressed in [44, 45]. Capture is good in the sense that it reduces the time needed in resolving collisions, but may also let weak terminals completely out of the medium. However, in satellite networks the near-far effect is typically very limited.

Figs. 1.2 and 1.3 present the performance results for S-ALOHA and DSA in the presence of packets power imbalance following i.i.d. lognormal distributions with equal mean μ and standard deviation σ with both parameters expressed in dB in the logarithmic domain. The results have been obtained by detailed simulations and by using the analytical model derived by the author in [47]. The x-axis represents the normalized average channel MAC load (G) expressed in information bits/symbol, in order to avoid any dependence with the modulation cardinality or coding rate used. As we can see, in both schemes the throughput improves with increasing power imbalance as collisions become easier to resolve (power capture effect). However, as expected, the packet loss ratio is not low and quickly increases as we increase the load on the channel. It can be remarked that for low loads (e.g. $G < 0.2$), DSA outperforms S-ALOHA. This can be better appreciated in Fig. 1.4, where S-ALOHA and DSA packet loss ratio curves are combined in one figure for the case of no power imbalance and the low load region is expanded. For instance, for a target $PLR = 10^{-2}$, DSA can achieve a throughput $T = 0.05$ while for S-ALOHA the maximum achievable throughput is $T = 0.01$. This is justified by the fact that under light traffic multiple transmission gives better PLR performance.

Slotted RA systems require terminals to keep the time slot synchronization. The resulting synchronization overhead greatly reduces the system efficiency, in particular for networks characterized by a large number of terminals with a very low transmission duty cycle like the case in some of the envisaged applications (M2M). Thus, slotted RA is penalizing low-cost terminal solutions. To mitigate this limitation, a pure ALOHA scheme can be employed, but its performance

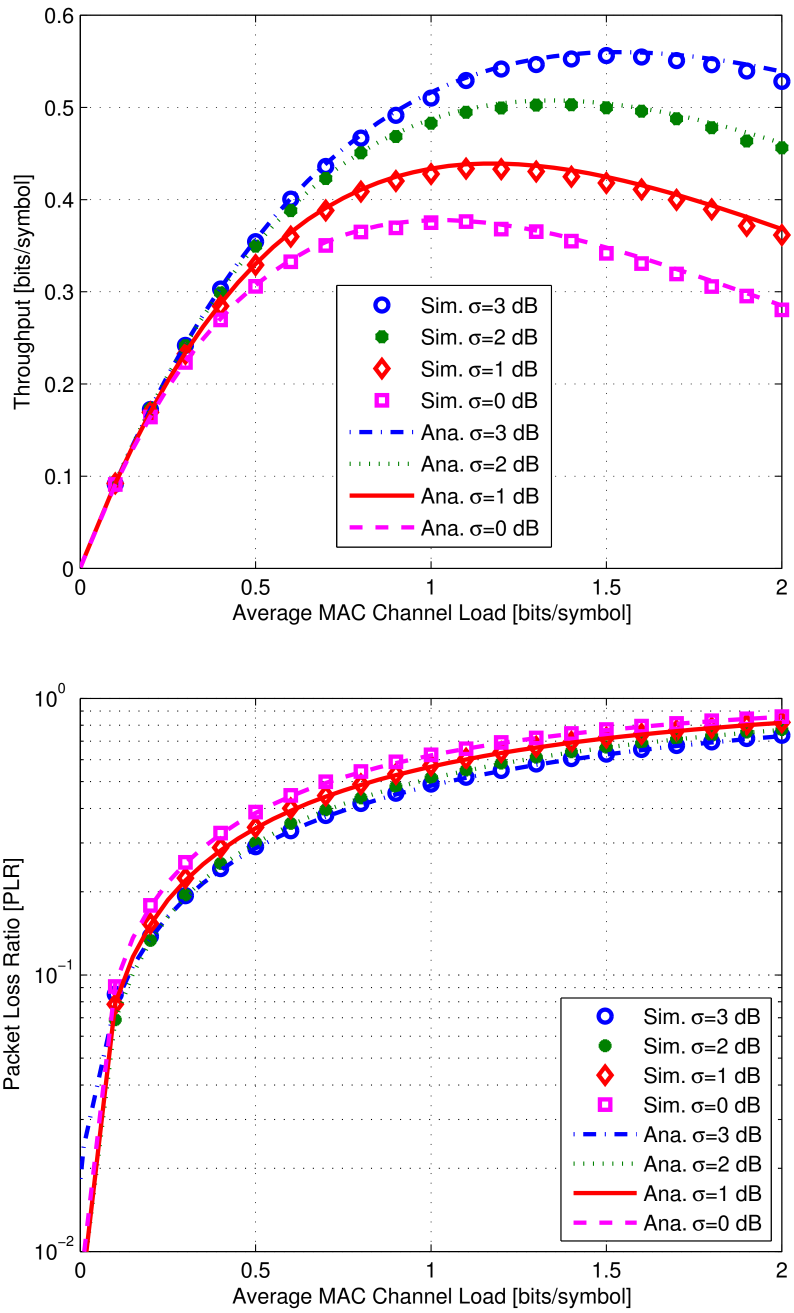


Figure 1.2: Analytical vs simulation S-ALOHA performance for QPSK modulation, 3GPP FEC $r = 1/2$, packet block size 100 bits, $E_s/N_0 = 7$ dB in the presence of lognormal packets power imbalance with mean $\mu = 0$ dB, standard deviation σ and Poisson traffic.

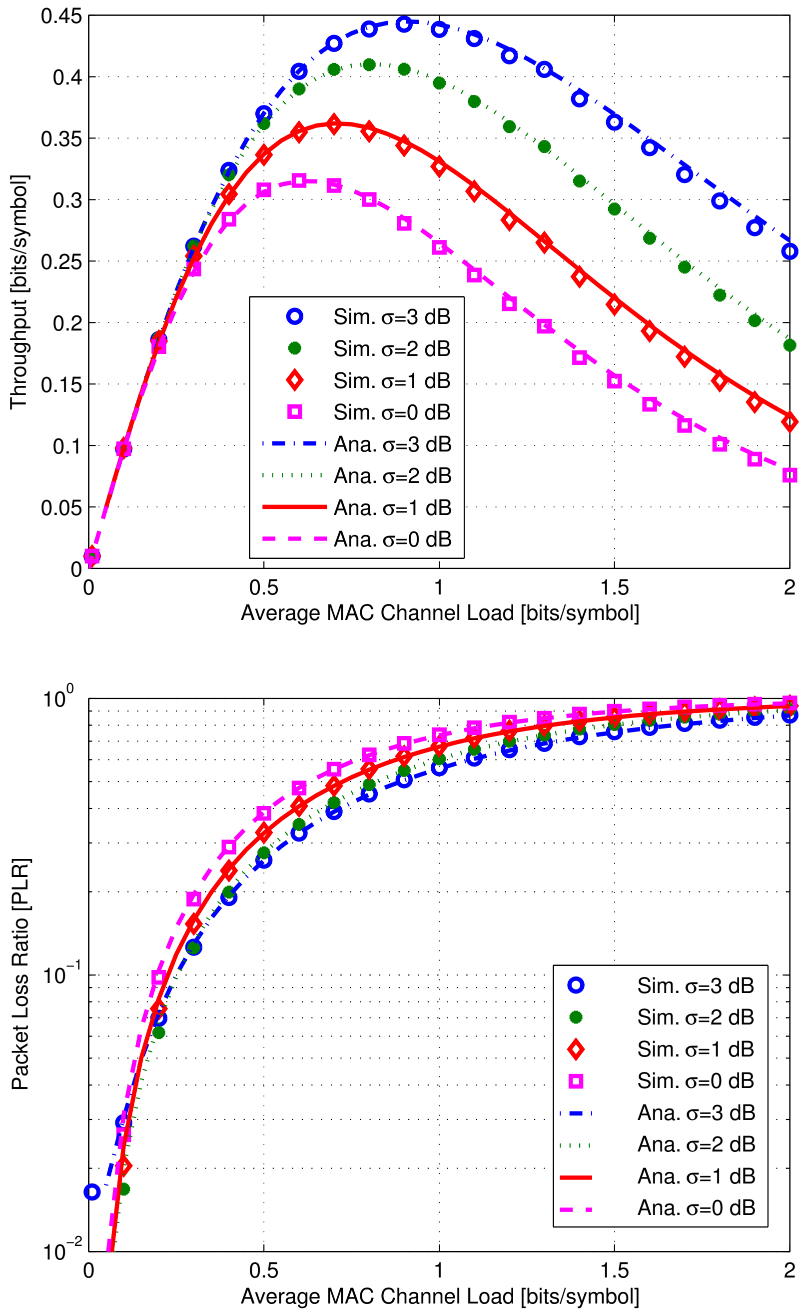


Figure 1.3: Analytical vs simulation DSA performance for QPSK modulation, 3GPP FEC $r = 1/2$, packet block size 100 bits, $E_s/N_0 = 7$ dB in the presence of lognormal packets power imbalance with mean $\mu = 0$ dB, standard deviation σ and Poisson traffic.

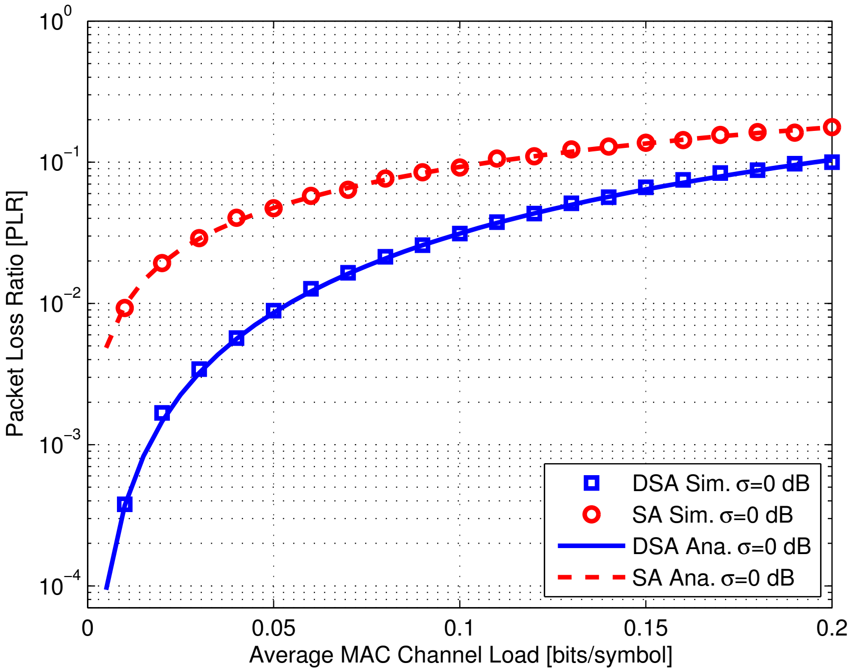


Figure 1.4: Analytical vs simulation S-ALOHA and DSA performance comparison in the low load region for QPSK modulation, 3GPP FEC $r = 1/2$, packet block size 100 bits, $E_s/N_0 = 7$ dB in the presence of no power imbalance and Poisson traffic.

is worse than for S-ALOHA increasing by two the packet collision probabilities [44].

Direct-sequence spread spectrum (DSSS) multiple access is the most common form of CDMA whereby each user is assigned a particular code sequence which is modulated on the carrier with the digital data modulated on top of that [8]. Users can transmit asynchronously. Even when the same code is used, data can be received [48, 49]. The Spread Spectrum ALOHA (SSA) proposed in [48] has potentially attractive features as it provides a higher throughput capability than S-ALOHA for the same PLR target under equal power multiple access conditions when adopting powerful physical layer FEC (e.g. coding rates $\leq 1/2$) and low order modulations (e.g. BPSK, QPSK). In [27] the author shows through simplified analyses that SSA throughput is critically dependent on the demodulator signal-to-noise plus interference (SNIR) threshold. Results reported in [27] indicate that differently from S-ALOHA, SSA shows a steep PLR increase with MAC load. Thus SSA can be operated with low PLR close to the peak of the throughput characteristic. As an example, using turbo codes and relatively small packets, SSA can achieve throughput in the order of $T = 0.5$ bits/chip for a packet loss ratio of 10^{-3} (see Fig. 1.5 with $\sigma = 0$ dB).

This is a very interesting random access scheme for the satellite environment, in particular when asynchronous access is considered. The main reason for the performance improvement of SSA techniques with regards to pure ALOHA is that they can take advantage of a higher traffic aggregation. The average number of packet arrivals over one packet duration can be computed as follows:

$$\lambda = N_{rep}\, G\, G_p, \tag{1.1}$$

where N_{rep} is the number of replicas transmitted for each packet, G is the MAC load expressed in information bits/symbol in non-spread systems and bits/chip in spread systems. The processing gain is given by $G_p = SF/(r \log_2 M)$ where r is the channel coding rate, M is the modulation cardinality and SF is the spreading factor.

It can be observed from eqn. (1.1) that large processing gains will increase the value of λ. Typical values for non-spread spectrum systems are $\lambda \leq 5$ while for spread-spectrum systems $\lambda \approx 100$. In Fig. 1.6 we can see that the Poisson PDF normalized to the mean, approaches a delta as we increase λ. This means that the instantaneous number of interfering packets will fluctuate less and less as we increase λ. This is favorable in RA because we can easily make the system to work around a desired load point (i.e. avoid having peaks of traffic) and also because interference can be accurately approximated as AWGN when we have a large number of interferer packets.

However, the SSA Achilles' heel resides in its high sensitivity to multiple access carrier power unbalance. This phenomenon is disrupting the SSA scheme throughput. The SSA throughput is diminished by several orders of magnitude when the received packets power is lognormally distributed with standard deviation of 2-3 dB (see Fig. 1.5), as opposed to S-ALOHA and DSA that improved performance with power imbalance due to the power capture effect. SSA is designed to work with MAI. Optimal power distribution for SSA is achieved when all packets have the same power level [27, 50]. When there is power unbalance the weakest packets may become not decodable (unless some interference cancellation technique is applied), thus reducing the RA throughput. DSA and S-ALOHA are designed to work with no or very little interference (collisions are in principle destructive). Under power imbalance some collisions can be recovered (capture effect), thus slightly improving the performance.

The above review of known terrestrial RA techniques reveals that none of them is fully performing over the satellite environment. Table 1.1 provides a summary of the different terrestrial RA techniques analyzed in this section. In general, terrestrial RA schemes are known to provide low channel utilization over the satellite environment due to the long propagation delays. Among all of them, the ALOHA-based techniques adapt better to the satellite environment, as they do not have any dependency on the propagation delay, but their performance is constrained by their high collision probability. As a result, today's satellite systems only use ALOHA-based RA for initial network login, capacity request and short packet transmissions [51, 52]. Therefore, it can be concluded that there is a need to develop new high-performance RA protocols to satisfy the growing market demands for satellite broadband access and M2M communications described in Sects. 1.1.1 and 1.1.2.

Technique	Main Characteristics
Carrier Sense Multiple Access (CSMA)	Carrier sense, reduced collision probability, sensitivity to propagation delay.
CSMA Collision Detection (CSMA/CD)	CSMA with reduced collision overhead.
CSMA Collision Avoidance (CSMA/CA)	CSMA with collision avoidance mechanism.
Multiple Access Collision Avoidance (MACA)	Distributed reservation, sensitivity to propagation delay.
MACA for Wireless (MACAW)	Distributed reservation, sensitivity to propagation delay.
Floor Acquisition Multiple Access (FAMA)	Distributed reservation and carrier sense, sensitivity to propagation delay.
Busy Tone Multiple Access (BTMA)	Distributed reservation, sensitivity to propagation delay.
3G Random Access Channel (RACH)	Distributed reservation, sensitivity to propagation delay.
Slotted ALOHA (S-ALOHA)	High collision probability, no dependency propagation delay.
Diversity Slotted ALOHA (DSA)	S-ALOHA with multiple copies, improved PLR under light traffic.
Spread Spectrum ALOHA (SSA)	Asynchronous CDMA, no dependency propagation delay, improved PLR under equal packets power.

Table 1.1: Summary of Terrestrial Random Access Techniques.

1.2 Goals

As described in Sect. 1.1, the improvement of Random Access (RA) protocols performance over satellite could bring great performance advantages to satellite communication networks in serving the growing demand for satellite broadband access and M2M communications. RA protocols provide fast access and are insensitive to the network population size and the traffic characteristics. Unfortunately, they offer poor channel utilization over the satellite environment due to the long propagation delays, as well as low reliability due to the high collision probabilities. As we have seen in Sect. 1.1.3, there is a big margin for improvement of RA schemes over satellite networks in terms of bandwidth utilization, which is typically not exceeding 0.05 bit/s/Hz if we want to achieve a target Packet Loss Ratio (PLR) $< 10^{-2}$.

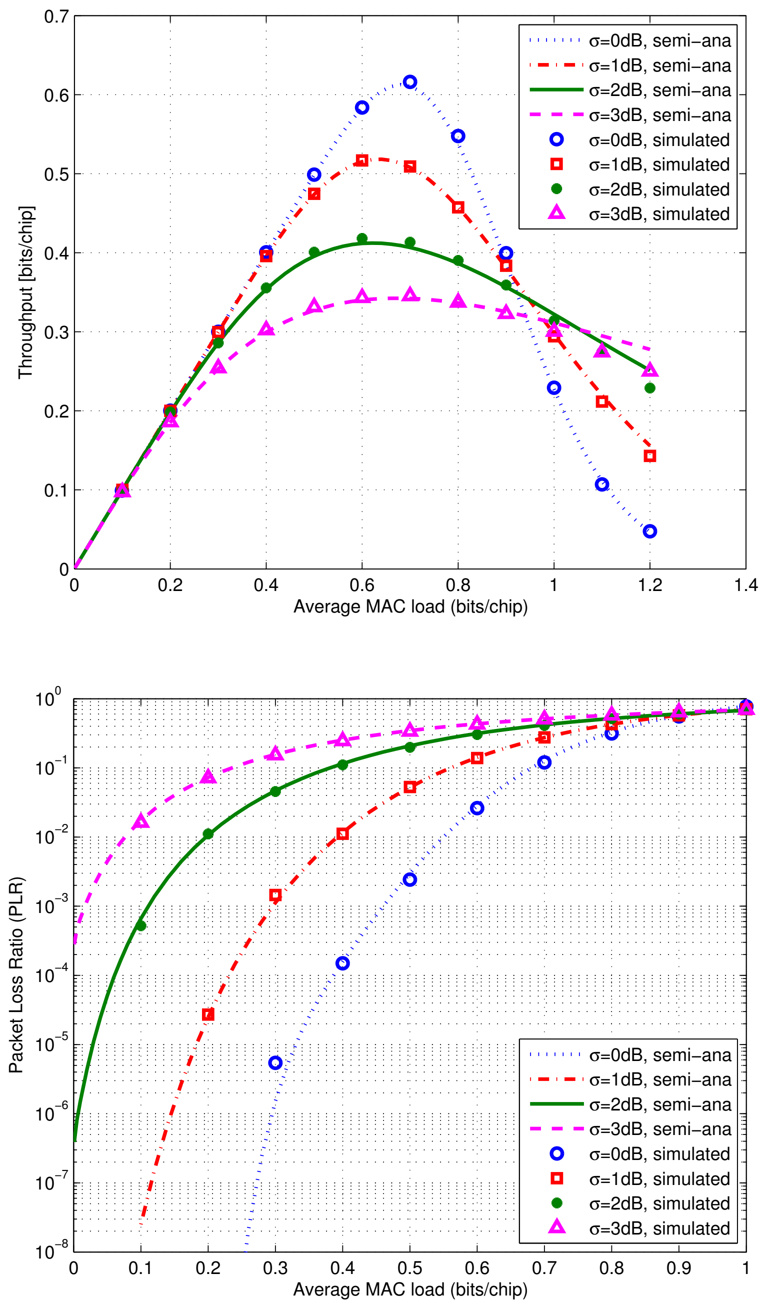


Figure 1.5: Simulated vs. Analytical SSA performance with and without power unbalance from [50]: 3GPP FEC $r = 1/3$ with block size 100 bits, BPSK modulation, spreading factor 256.

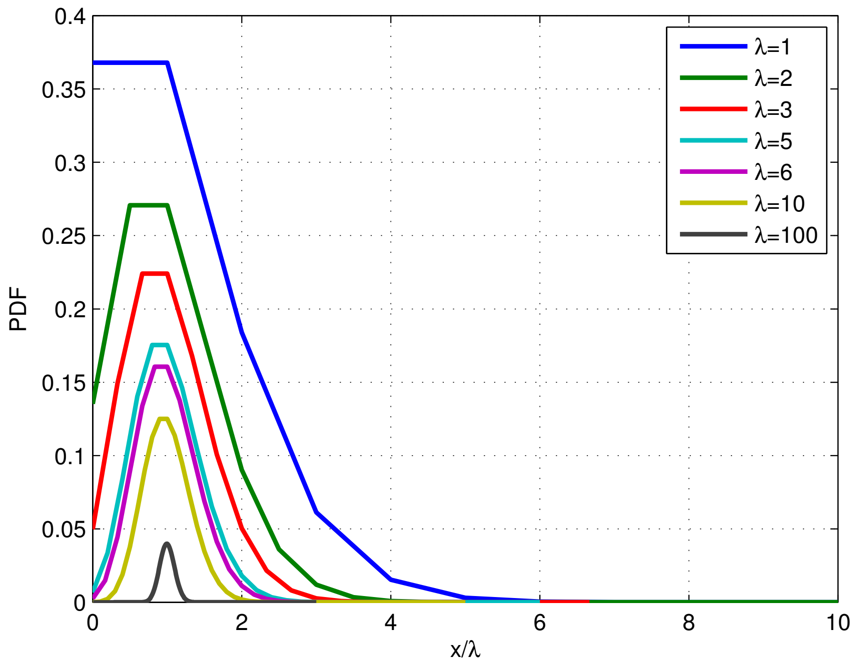


Figure 1.6: Traffic probability distribution normalized to the mean value.

The main goal of this thesis is to investigate new RA schemes well suited for the satellite environment that can offer high channel efficiency (e.g. > 1 bit/s/Hz aggregate spectral efficiency) and reliability ($PLR \leq 10^{-3}$) while keeping very low access delays (in the order of 1 satellite hop delay) and low implementation complexity (comparable to today's RA solutions). It should be recalled that the satellite beam area is typically very large compared with the terrestrial networks cells, i.e. from several hundreds to a few thousands kilometers of diameter. The new RA protocols shall be robust to operate with very large number of communicating terminals (e.g. several thousands) sharing the same bandwidth. The new schemes shall also be robust to power imbalance inherent to the satellite communication channel (e.g. due to shadowing and multipath fading). Since we are aiming at low cost, low power and small size earth stations, the new RA schemes require low complexity on earth stations side and shall keep the advanced processing in the receiver side (e.g. in the hub). In addition, both slotted and asynchronous (spread and non-spread) access shall be considered in order to leverage on existing communication standards (e.g. MF-TDMA or CDMA based systems).

Chapter 2

The work

In this thesis, the author presents new advanced random access techniques derived from the ALOHA protocols that boost their performance over the satellite environment and enable new market opportunities for satellite communications. As we have seen in Sect. 1.1.3, the RA techniques that best adapt to the satellite environment are the ALOHA-based techniques, as they do not have any dependence on propagation delay. This imposes that the new RA schemes shall be able to operate under very high packet collision conditions.

To achieve that goal we shall exploit the advances in signal processing techniques such as interference cancellation (IC) and strong forward error correction (FEC) coding techniques. The multiuser detection research area covers many different algorithms for mitigating interference between users [53]. While classical IC often assumes synchronous CDMA continuous transmission, this thesis addresses the cases of IC for asynchronous bursty transmissions (spread and non-spread spectrum based), as well as TDMA-based systems. This thesis investigates coordinated IC processing techniques at a common receiver (e.g the hub) with the aim of achieving an aggregated data rate of all simultaneous users approaching the Shannon capacity of the Gaussian noise channel, even for the asynchronous case. The choice of the physical layer FEC scheme for RA systems is not as straight-forward as for conventional communication systems operating in Additive White Gaussian Noise (AWGN). Being a RA Multiple Access (MA) system, the individual but also the aggregate MA performance are relevant. FEC coding schemes shall operate in front of strong interference and not always under AWGN-like conditions (e.g. for TDMA based systems). Therefore lower coding rates, although apparently reducing the individual packet bit rate, may be important to enhance the overall RA scheme performance. This thesis investigates the impact of the FEC coding rate on the RA protocols performance. As explained in Sect. 1.1.3, the level of traffic aggregation in TDMA-based systems is much lower than in CDMA ones. This means that the instantaneous number of interfering packets in TDMA-based systems fluctuates a lot and we cannot guarantee to operate under a desired working point. This thesis investigates novel approaches to introduce time diversity in TDMA-based systems in order to improve the collision probability conditions. The complexity of the new proposed techniques is analyzed to ensure they are commercially viable.

This thesis also analyses the performance of the new proposed RA techniques and compares them with traditional RA protocols. RA analytical results for conventional RA schemes presented so far were assuming uncoded systems and equi-powered interfering packets [43, 44], which is not what is required in modern satellite communication systems. Some analysis of the power capture effect is reported in [45, 54, 55, 56], but existing models are limited to discrete power levels, do not provide an accurate modeling of the RA Forward Error Correction (FEC) behavior, and more importantly, do not include IC. This thesis defines new RA analytical frameworks that allow calculating the performance of traditional and new RA techniques in terms of PLR and throughput. The proposed frameworks assume arbitrary power and traffic distributions, and accurately model the RA FEC and IC behavior. Analytical results have been successfully compared to a wide set of simulation results showing the capability of the proposed analytical framework to predict the the RA scheme performance in the vast majority of application cases.

The contributions have been grouped into slotted and asynchronous RA techniques and are summarized in the following sections.

2.1 Slotted Random Access

Research for slotted RA techniques took place between 2005 and 2009, and then complemented by an analytical framework in 2014. The research on slotted systems was triggered by the need to introduce efficient and reliable RA schemes to the existing satellite systems using standards for interactive satellite broadband networks like the Digital Video Broadcasting (DVB) Return Channel via Satellite (DVB-RCS) [51] and the Telecommunication Industry Association (TIA) IP over Satellite (IPoS) [52]. The standard-based and many proprietary satellite communication systems employ MF-TDMA access and rely primarily on DAMA schemes for the transmission of data traffic on the return link (earth station to hub), as described in Sect. 1.1.2. The arrival of broadband Internet access for the consumer market introduced the need for a fast satellite access to a very large population of earth stations sharing the same bandwidth.

The first contribution from the author is a RA scheme dubbed Contention Resolution Diversity Slotted Aloha (CRDSA) [57] and included in this thesis in chapter 4. The CRDSA technique consists in transmitting every burst two or more times (N_{rep}) in randomly selected slots within a TDMA frame of N_{slots}. Each burst contains in the header information of the location of the replicas within the frame (see Fig. 2.1). The transmitter achieves network synchronization in the same way as it is defined in the MF-TDMA based standards [51, 52], i.e. the terminal exploits the forward link network clock reference required for MF-TDMA terminal time reference generation to also generate time and frequency reference for CRDSA.

The complete TDMA frame is sampled and stored in a digital memory at the receiver side. By using simple yet efficient interference cancellation techniques, clean bursts are recovered (e.g. packet 3 in slot 5 in Fig. 2.1) and the interference generated by their replicas on other slots are cancelled (e.g. packet

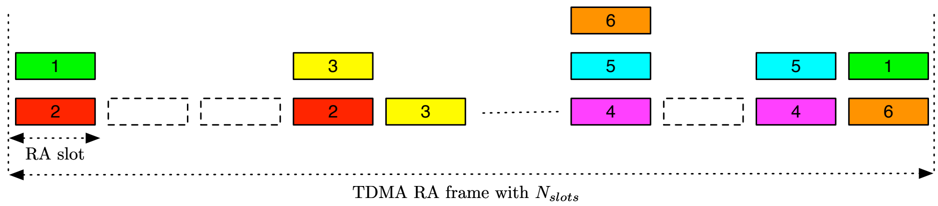
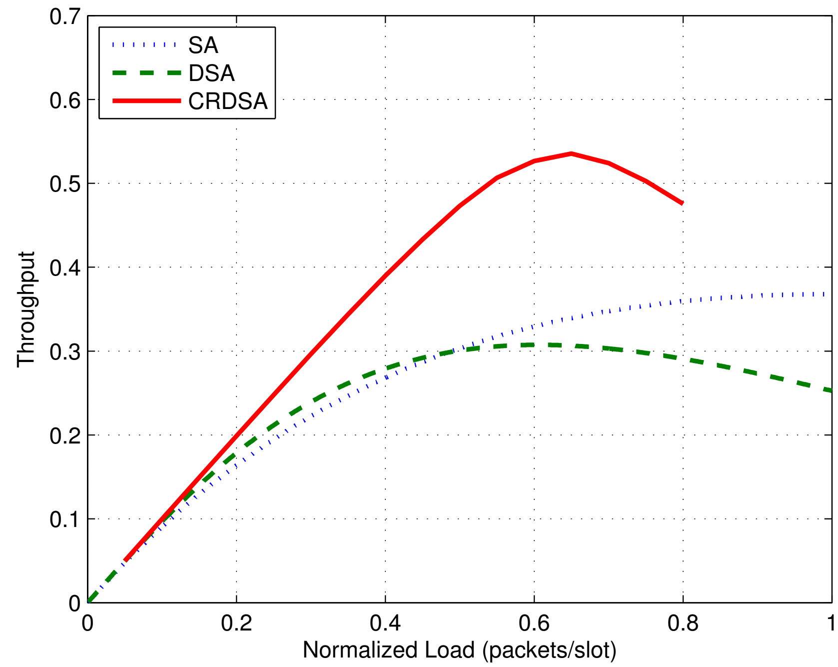


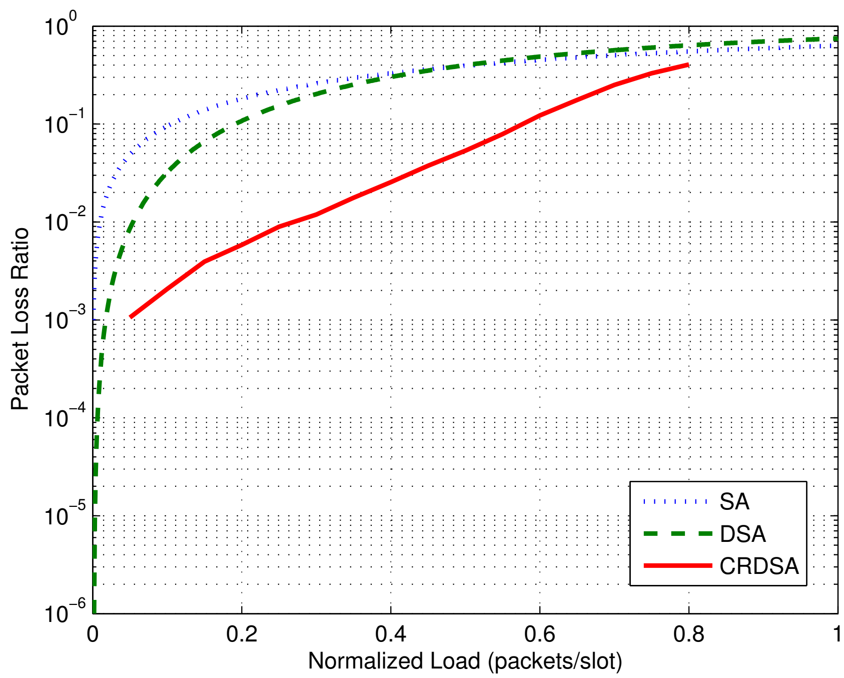
Figure 2.1: Example of CRDSA frame with two replicas per packet.

3 in slot 4). By performing an iterative processing of the TDMA frame it is proven that most of the initial collisions can be resolved. In Fig. 2.2 it is shown that CRDSA largely outperforms classical Slotted Aloha techniques in terms of throughput and packet loss ratio (PLR). For a MAC packet loss probability of 2%, channel utilization efficiencies close to 40% can be achieved with the CRDSA technique (see Fig. 2.2(b)), while for S-ALOHA only a channel utilization efficiency of 2% can be achieved for the same packet loss probability (see Fig. 1.4). This represents a 20-fold throughput improvement compared to S-ALOHA. It is important to highlight the importance of PLR improvement in the satellite environment, as it has a direct benefit on the end-to-end delay due to a reduction in the need for packet retransmissions. The author's contribution [57] presents detailed performance results on delays.

The performance boost of the CRDSA protocol is achieved thanks to the implementation on the hub receiver of a collision resolution capability that exploits IC techniques. IC techniques have been largely investigated for Code Division Multiple Access (CDMA) [53] but, at the author's knowledge, have never been proposed in a TDMA S-ALOHA context. CRDSA is basically a TDMA access scheme that uses the information from the successfully decoded packets to cancel the interference their replicas may generate on other slots. We are able to cancel the interference because we know the data symbols of the interference from the successfully decoded packets. One of the main issues in applying IC techniques to TDMA S-ALOHA is related to the need for accurate channel estimation for the burst replicas removal where collision(s) occur. In fact, collisions in a satellite TDMA multiple access channel are typically destructive as the near-far effect is rather limited. While carrier frequency, amplitude and timing estimation for IC can be derived from the "clean" replica (e.g. packet 3 in slot 5 in the example from Fig. 2.1), carrier phase has to be estimated on the slot where collision(s) occurs (e.g. in slot 4). This is because the phase in practical broadband systems is time variant also from slot to slot. This key problem has been solved in [57] by exploiting the burst preamble which is individually "signed" by a pseudo-random binary sequence randomly selected among the available code family by each active earth station for each burst in each frame. All replicas of the same burst use the same preamble code. This approach does not require a centralized preamble code assignment, thus allowing to maintain the random access nature of the proposed scheme. In this way the preamble can be used for carrier phase



(a) Throughput versus load



(b) Packet Loss Ratio versus load

Figure 2.2: Simulation S-ALOHA, DSA and CRDSA performance for $N_{rep} = 2$, $N_{slots} = 100$, QPSK modulation, 3GPP FEC $\rho = 1/2$, packet block size 100 bits, $E_s/N_0 = 7$ dB in the presence of no power imbalance and Poisson traffic.

estimation also in case of multiple collisions which normally are destructive for channel estimation and payload decoding. With the above channel estimation implementation, it is shown in Section V.C in from [57] that CRDSA performance results on non-ideal channel estimation for IC are very close to those derived with ideal channel estimation.

An alternative way to perform channel estimation is to use a single Unique Word (UW) for all bursts and all earth stations, but use some of the payload symbols, which are known from the clean replicas, for carrier phase estimation. Payload symbols are uncorrelated among the colliding packets, even though without excellent cross-correlation properties. It is found that by using payload symbols for carrier phase estimation, performance results are comparable to those obtained by using multiple pseudo-random binary sequences for the burst preambles. But his approach reduces complexity on both the earth stations and hub as a single UW is used. Besides, the knowledge of the payload data allows to track the carrier phase along the burst by using an normal Data Aided-Phase Locked Loop (DA-PLL), which is particularly useful when low cost terminals with very low baud rate are used (e.g for interactive TV), since the RF front ends introduce a phase noise (nuisance) making the carrier phase not constant over the burst duration. This improvement was proposed by Daniel Delaruelle from NEWTEC and Jean Pierre Choffray from SES-ASTRA. Both channel estimation approaches have been extensively investigated in [58] (see chapter 6).

Prior to the IC of a packet, the whole packet is re-modulated allowing data aided refined amplitude and phase estimation. This maximizes the IC efficiency with a minimal degradation of the CRDSA performance when compared to ideal channel estimation conditions [58].

CRDSA has a number of parameters that can greatly influence their performance, being the most important ones FEC coding rate ρ, the number of replicas N_{rep} and the packets power imbalance. With the aim of optimizing its performance, the author has developed an analytical framework and a detailed simulator for the performance assessment of slotted RA protocols (see [47] included in this thesis in chapter 5). The proposed analytical framework assumes arbitrary power and traffic distributions, and accurately models the FEC and RA IC behavior. To be remarked that using a powerful FEC code (e.g. $\rho = 1/3$) and an adequate signal to noise ratio (e.g. $SNR = 10$ dB), there is non zero probability of correctly detecting the packet even in presence of a collision (capture effects). Besides FEC coding schemes shall operate in front of strong interference and not always under AWGN-like conditions (e.g. for TDMA based systems). When payload burst are protected by a powerful FEC, a phase estimation error standard deviation up to 15 degrees can be tolerated without significant impact on the performance [58]. Therefore lower coding rates, although apparently reducing the individual packet bit rate, are very important to enhance the overall RA scheme performance. Three burst replicas gives better performance than two, because it significantly reduces the loop occurrence probability between packets from different earth stations. In the example if Fig. 2.1, packets 4 and 5 have formed a loop as their replicas have been transmitted in the same slots. The issue of loops has been extensively analyzed by the author in [47], and with three packet replicas the probability of occurrence is well below the packet loss ratio target for our applications ($PLR < 10^{-3}$). Packets power imbalance greatly contributes to the interference cancellation process and boosts the performance of CRDSA. Strong packets are decoded first and weaker packets are successively decoded following the iterative IC process. Power imbalance results from the combined effect of the time variant atmospheric propagation, open loop power control errors (if applicable), earth station equivalent isotropically radiated power (EIRP) and satellite receive antenna gain variations. It is shown in Fig. 2.3 that CRDSA with FEC $\rho = 1/3$, $N_{rep} = 3$ and power imbalance following a lognormal power distribution with standard deviation $\sigma = 3$ dB, can achieve a throughput $T = 1.4$ bits/symbol for a $PLR < 10^{-3}$, which represents a 1400-fold improvement with respect to S-ALOHA.

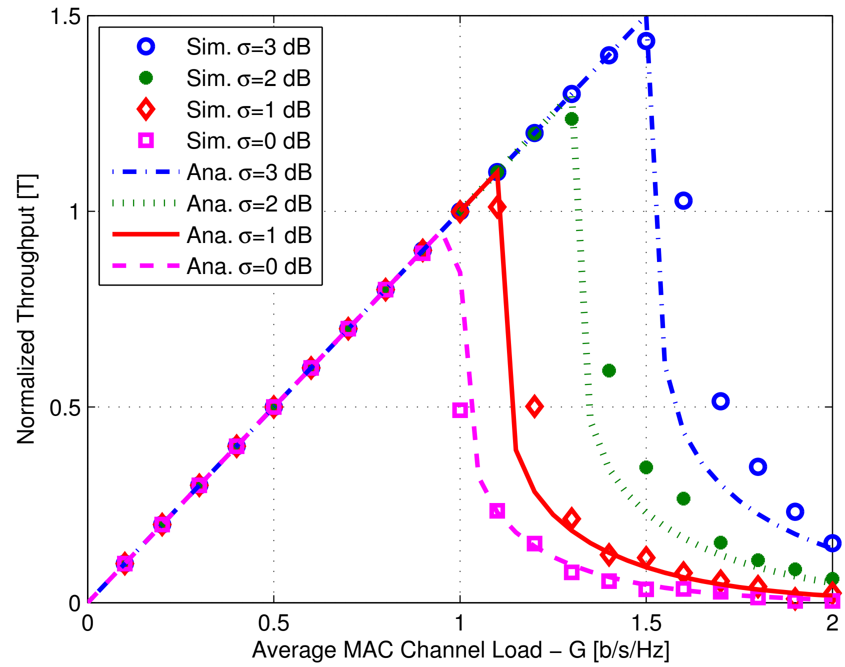
2.2 Asynchronous Random Access

Research on asynchronous random access took place between 2008 and 2014. The research on asynchronous access was triggered by the growing demand for low cost and highly efficient solutions supporting both fixed and mobile satellite services, such as consumer broadband access, machine-to-machine communications (M2M), interactive TV, supervisory control and data acquisition (SCADA), transaction and safety of life applications. These networks are generally characterized by a large population of low power and small size terminals, sharing the available resources under very dynamic traffic conditions. In particular, in the return link (earth station to hub) users are likely to generate low duty cycle bursty traffic with extended inactivity periods. Slotted RA systems require terminals to keep the time slot synchronization through a control loop. The resulting synchronization overhead can greatly reduce the system efficiency, in particular for networks characterized by a very large number of terminals with a very low transmission duty cycle, like it is the case in some of the envisaged applications (e.g. M2M). Thus, slotted RA is penalizing low-cost terminal solutions. To mitigate this limitation, asynchronous RA schemes are preferable.

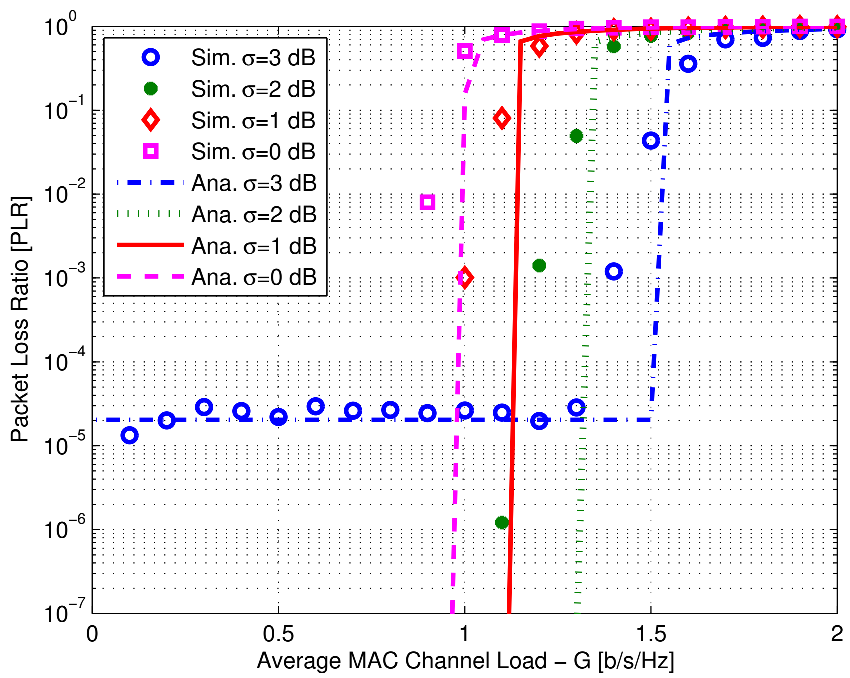
Asynchronous RA schemes can been divided into spread spectrum and non-spread spectrum multiple access techniques. This thesis presents two novel asynchronous RA schemes. The first one, dubbed Enhanced Spread Spectrum ALOHA (E-SSA), is an extension of Spread Spectrum ALOHA presented in Section 1.1.3 and introduces an IC mechanism at the receiver. The second RA technique, Asynchronous Contention Resolution Diversity ALOHA (ACRDA), is an extension of the CRDSA protocol presented in Sect. 2.1 to a truly asynchronous multiple access environment. ACRDA is non-spread spectrum based, but incorporates some of the E-SSA receiver processing functions to support the asynchronous access from all the earth stations to the shared medium.

2.2.1 Enhanced Spread Spectrum ALOHA

Enhanced Spread Spectrum ALOHA (E-SSA) behaves like SSA on the transmitter side (see Sect. 1.1.3). The E-SSA novelty lies on the detector [59]. The



(a) Throughput



(b) PLR

Figure 2.3: Analytical vs. Simulation CRDSA performance for $N_{\text{rep}} = 3$, $N_{\text{max}}^{\text{iter}} = 15$, N_{slots}=1000, QPSK modulation, 3GPP FEC $\rho = 1/3$, packet block size 100 bits, $E_s/N_0 = 10$ dB in the presence of lognormal packets power unbalance with mean $\mu = 0$ dB, standard deviation σ and Poisson traffic [47].

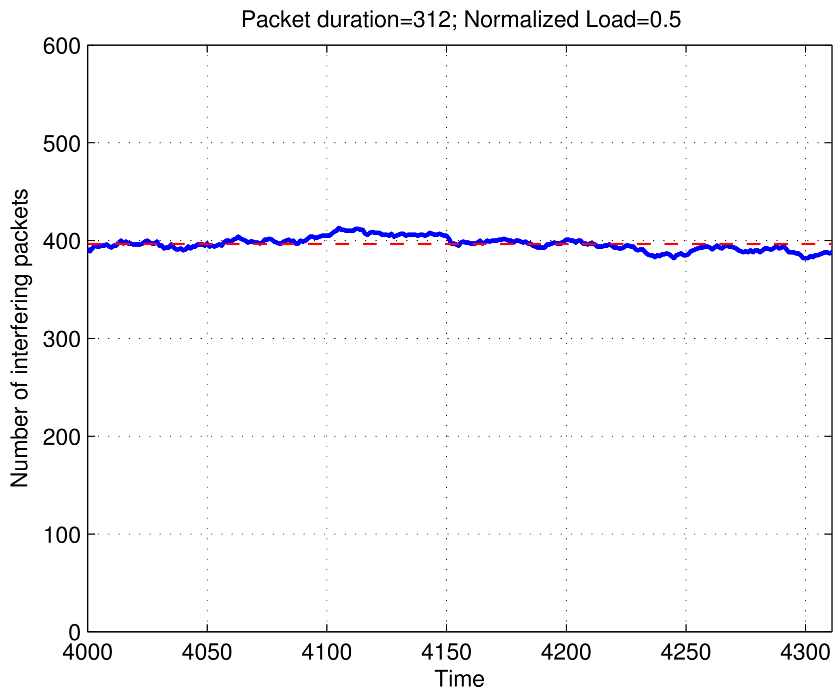


Figure 2.4: Realization of the instantaneous and average number of interfering packets over packet of interest [60].

detector located at the hub is the heart of the system, as it has to support a high throughput of incoming packets. For a typical spread spectrum system with $N_{rep} = 1$, $SF = 256$, $r = 1/3$, $M = 2$ and a normalized load $G = 0.5$, the average number of packet arrivals over a packet duration is $\lambda = 384$ (see eqn. (1.1)), which represents quite a large value. In Fig. 2.4, the author shows that the instantaneous number of interfering packets is almost constant around the mean value $\lambda = 384$ (red line) over the whole packet duration. This is advantageous for a RA scheme design because the interference can be accurately approximated as AWGN when we have a large number of interferer packets. The time on the x-axis corresponds to symbol time steps, and the packet shown in this example is a 100 bit packet with 300 coded bits. The complete set of system parameters used for the E-SSA analyses can be found in Table I from [50], also included in this thesis in chapter 7.

The principle of the E-SSA detector is illustrated in Fig. 2.5. The received CDMA signal is band-pass filtered, sampled, digitally down-converted to baseband with I-Q components separation and stored in a digital memory of $2 \cdot W N_s^c$ real samples. We assume that complex baseband samples are stored in I-Q format. N_s^c corresponds to the number of chips per physical layer channel symbol and W corresponds to the memory window size in symbols for the interference cancellation process at the hub. The window size W shall be optimized to be the smallest possible value yielding good IC performance. Typically, W should

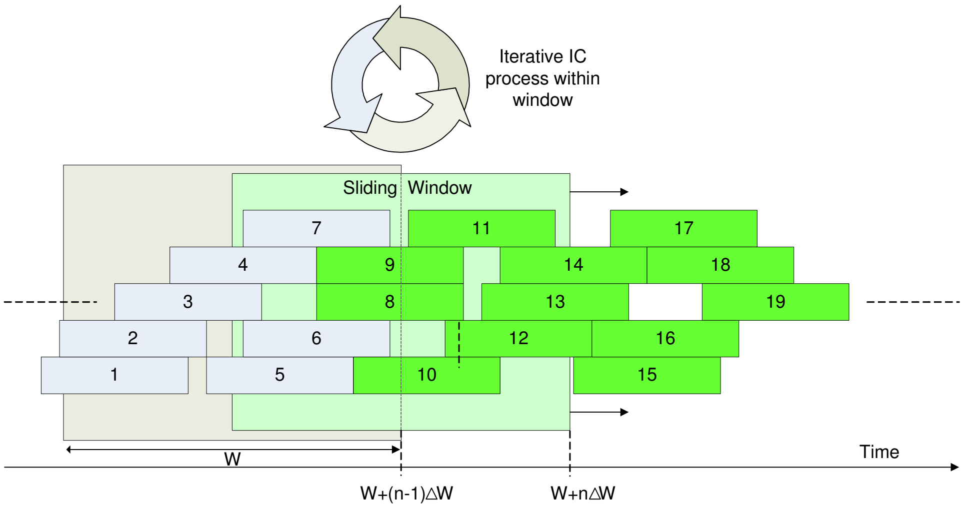


Figure 2.5: Enhanced Spread Spectrum Aloha algorithm description.

be three times the physical layer packet length in symbols. The receiver window memory is shifted in time in discrete steps allowing some overlap of packets on each window step (sliding window process). To reduce the detector complexity the window step ΔW, in symbols, shall be the largest possible yielding a good IC performance. Normally, the window step ΔW shall be between $1/3$ to $1/2$ of the window length W depending on its size. At each window step, the following iterative Successive Interference Cancellation (iSIC) process takes place:

1. Store in the detector memory the new baseband signal samples corresponding to the current window step (n);

2. Perform packets preamble detection and select the packet with highest Signal to Noise plus Interference Ratio (SNIR) value;

3. Perform data-aided channel estimation for the selected packet over the preamble;

4. Perform FEC decoding of the selected packet;

5. If the decoded FEC frame is considered correct after CRC check then:

   (a) Perform enhanced data-aided channel estimation over the whole recovered packet (carrier frequency, phase, amplitude, timing);

   (b) Reconstruct at baseband the detected packet for following cancellation step;

   (c) Perform interference cancellation;

6. Repeat from step 2 until $N_{it\,max}^{W}$ iterations are performed. When the limit is reached, advance the observation window by ΔW.

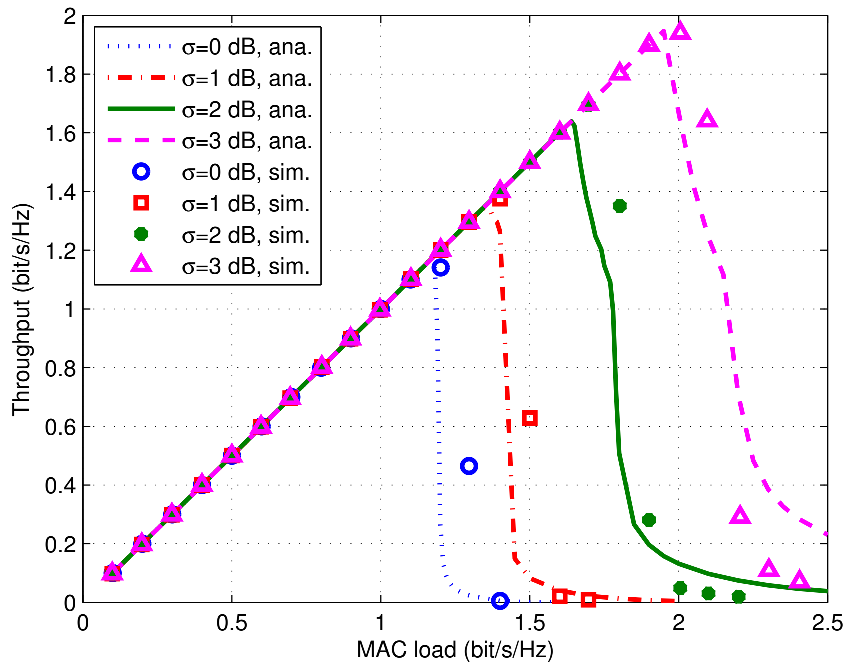
A detailed analytical description of the E-SSA algorithm is provided in Appendix I from [50], also included in chapter 7 of this thesis. Two important steps for an optimal E-SSA performance are the packet preamble detection in front of very high interference (step 2) and the IC process defined in step 5(c). The hub demodulator starts searching for the presence packet preamble by means of a conventional preamble correlator. Because of the incoming packets carrier frequency uncertainty due to the oscillator instabilities, preamble parallel search in the frequency domain is typically required. The preamble acquisition performance needs to be lower than the target PLR (e.g 10^{-3}) in terms of the probability of missed detection P_{md} and the probability of false alarm P_{fa} at the very high MAC operating load allowed by E-SSA. Preamble acquisition aspects have been summarized in Sect. IV.E in [50]. A particular aspect in SS is the need for a longer preamble for packet detection due to operation under very high MAI ($E_c/(N_0 + I_0) \approx -30$ dB). When a preamble is detected, the associated packet amplitude, carrier frequency, chip timing and phase are estimated exploiting the preamble plus possible auxiliary pilot symbols. At this point, despreading, coherent detection, payload and signalling bits decoding takes place. This demodulation step is comparable to a conventional DS-SS burst demodulator. The transmitted packet contains also a CRC, which is exploited by the demodulator to verify that the packet has been correctly detected. If this is the case, the payload information is extracted. At the same time the decoded bits are re-encoded and re-modulated. This locally regenerated packet is then correlated with the memory samples corresponding to the currently detected packet location. Through this correlation process it is possible to extract a more accurate amplitude and carrier phase estimation compared to the initial demodulation step. This is because the replica packet(s) amplitude and phase estimation is now extending over the whole packet duration instead of being limited to the sole preamble length. In this way, amplitude and phase variations over the packet duration can be estimated resulting in a more accurate cancellation process. This key step is called payload data-aided refined channel estimation and is the same used for CRDSA IC [58]. Thanks to the refined channel estimation, the E-SSA demodulator achieves accurate cancellation of the detected packet from the sliding window memory.

The E-SSA performance has been investigated in-depth both by analysis and simulation in Sect. IV.D from [50]. The analytical framework proposed by the author, accurately models the performance of spread-spectrum RA techniques, such as SSA and E-SSA, and assumes arbitrary power and traffic distributions, and accurately models the FEC and RA IC behavior (see Section IV.A from [50]). Fig. 2.6 reports some key conclusion about E- SSA performance. Performance results shall be compared to the SSA ones reported in Fig. 1.5. First of all, assuming a target PLR of 10^{-3} and no power imbalance, the E-SSA throughput is 1.12 bits/symbol, i.e. 2.4 times higher than conventional SSA. When lognormal distributed packet power is assumed (with standard deviation $\sigma = 2$ dB), then the E-SSA throughput reaches 1.7 bits/symbol, i.e. 17 times larger than SSA. This striking result is due to the iSIC superior performance compared to a conventional SSA burst demodulator in case of imbalanced power. The received packets power fluctuation at the hub is caused by the uplink Land Mobile Satellite (LMS) channel shadowing and multipath fading, as well as the satellite and earth station antenna gain variations as a function of the location. In Sect. VI from [50], Riccardo De Gaudenzi proposes a SNIR driven uplink packet transmission control (SDUPTC). SDUPTC is based on the principle to transmit packets only when the downlink signal quality is good enough, i.e. the signal strength or better SNR is within a certain window representative of Line-of-Sight (LOS) conditions. If this is not the case the transmission is delayed until (quasi)-LOS conditions are verified. The proposed simple SDUPTC algorithm is intended to maximize the probability of packet successful transmission, limit the power imbalance among the packets received at the hub side to improve the RA scheme performance and to avoid creating multiple access interference (MAI) when not useful for packet transmission.

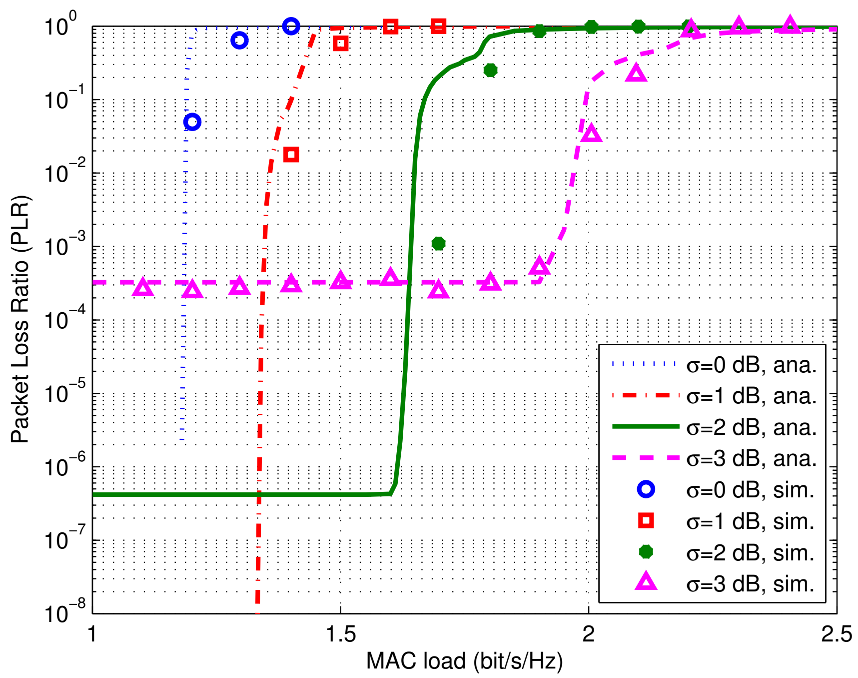
2.2.2 Asynchronous Contention Resolution Diversity ALOHA

The Asynchronous Contention Resolution Diversity ALOHA (ACRDA) protocol is analyzed in detail in [61], and included in this thesis in chapter 9. An introduction to the ACRDA patent [62] is also presented in chapter 10. Unlike S-ALOHA, DSA or CRDSA, ACRDA eliminates the need to maintain accurate slot synchronization among all transmitters, but differently to SSA and E-SSA, does not require the use of spread spectrum techniques. The need for transmitter synchronization is a major drawback for very large networks (e.g. M2M), as the signaling overhead scales up with the number of transmitters independently from their traffic activity factor.

In ACRDA, earth stations behave like in CRDSA, exploiting packet replicas and the associated location signaling, but do not need to maintain slot synchronization with the hub. The term *Virtual Frame* (VF) is introduced here to refer to the concept of frame of slots that is only local to each transmitter. In ACRDA, for all transmitters, each VF is composed of a number of slots N_{slots} and each slot has a duration T_{slot} with an overall frame duration $T_{\text{frame}} = N_{\text{slots}} \cdot T_{\text{slot}}$. Fig. 2.7 shows the Virtual Frame compositions for the ACRDA scheme. The different transmitters are not time synchronized, and hence, the time offset between VF(i), VF($i-1$), VF($i+1$) is arbitrary. In case of mobile applications, the Doppler effect may have an appreciable impact in terms of incoming packets clock frequency offset. In this situation the VFs will have slightly different duration. However, the localization process of the replica packets within each VF will remain accurate, as the hub burst demodulator will extract for each VF its own clock reference. Since the demodulator has no knowledge of the start of VFs, the signaling of the replicas location within the VF has to be relative to each packet position and not absolute to the start of the VF. Two options exist for the ACRDA modulator (as described in Sect. II.A from [61]), which consist in transmitting all packet replicas randomized within the VF, or transmitting the first packet replica in the first slot of the VF and the remaining replicas randomized within the VF. The latter option, improves end-to-end delay performance since first packet replica is transmitted without any added delay.



(a) E-SSA Throughput with and without power unbalance.



(b) E-SSA PLR with and without power unbalance.

Figure 2.6: Simulated vs. Analytical E-SSA performance with and without power unbalance, 3GPP FEC $r = 1/3$ with block size 100 bits, BPSK modulation, spreading factor 256 [50].

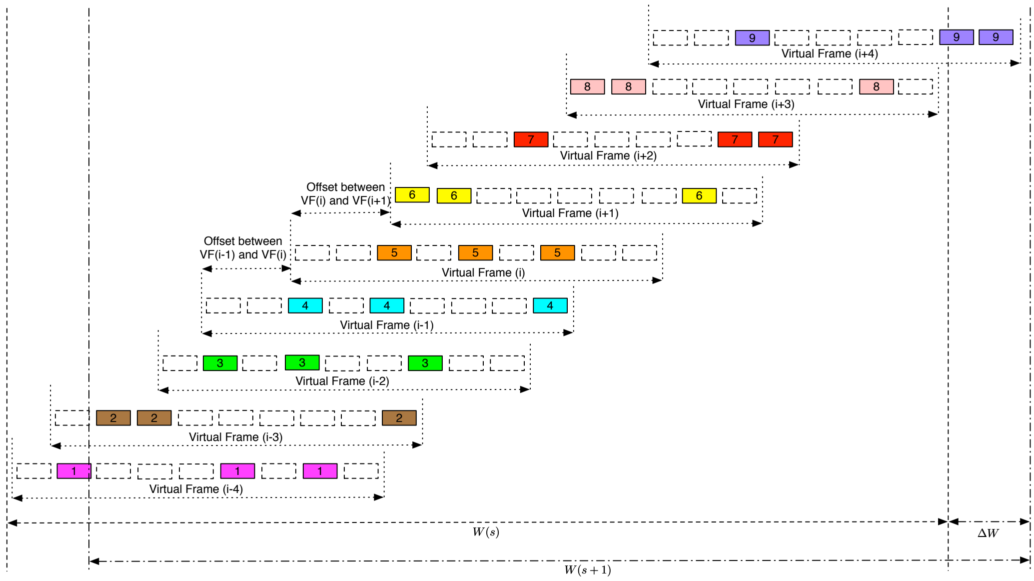


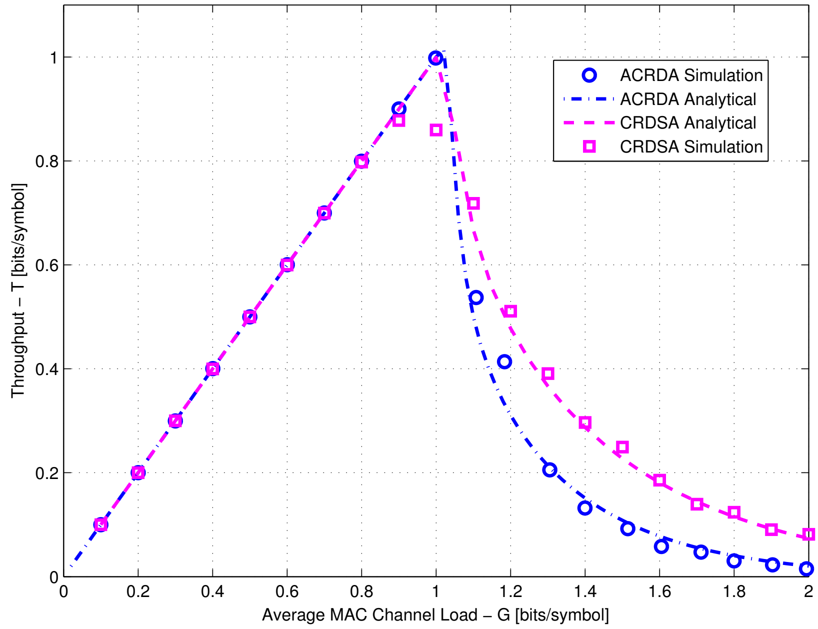
Figure 2.7: Virtual frame compositions in ACRDA.

ACRDA combines features of CRDSA, and E-SSA on the receiver side. On one hand, the same E-SSA sliding window-based memory processing described in Sect. 2.2.1 is adopted to handle the asynchronously arriving packet replicas. On the other hand, for a given receiver memory position, the replica packets cancellation scheme described in Sect. 2.1 is borrowed from the CRDSA demodulator processing. The received signal is sampled at baseband, and complex signal samples are stored in a sliding window memory of W virtual frames (see Fig. 2.7). Typically $W = 3$ for optimal ACRDA performance, as for E-SSA. For a given window position, the demodulator performs the same iterative processing as for CRDSA to decode the clean packets and perform IC of the replica packets. The detailed ACRDA demodulator operation is described in Sect. II.B from [61]. Once the iterative processing of a specific window position is completed, the sliding window is shifted towards the right in time by ΔW, which is a fraction of the VF duration (e.g. $\Delta W = 1/6$). The oldest samples spanning the leftmost part of the memory will be removed and the emptied rightmost part of the memory will be then filled with the new incoming complex samples.

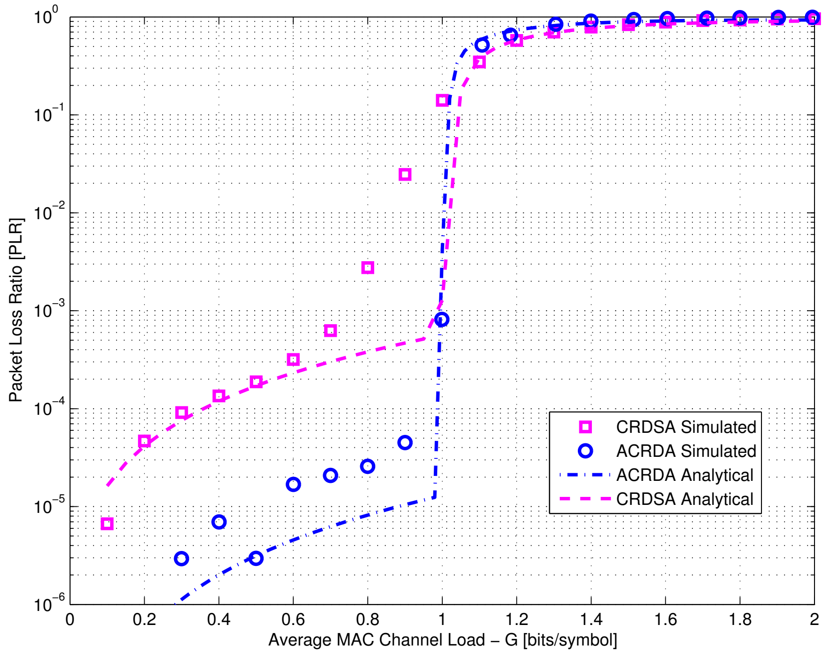
ACRDA provides better PLR and throughput performance than CRDSA. Fig. 2.8 compares the performance of the ACRDA vs. CRDSA, evaluated via mathematical analysis and computer simulations. Similarly to the other proposed RA schemes, the author proposes in Sect. III from [61] an analytical framework derived from the RA analytical framework presented in [47]. For a target $PLR = 10^{-3}$, ACRDA channel can be loaded up to 1 bits/symbol, while CRDSA not more than 0.75 bits/symbol. It is important to note that the PLR floor present at low loads (i.e. $G < 1$ bits/symbol) is lower for ACRDA than CRDSA. The reason for this is that the probability of loops occurrence, described in Sect. 2.1, is significantly lower in ACRDA than in CRDSA due to the asynchronous nature of the access. The effect of loops in performance is analyzed in detail in Sect. III from [61] for ACRDA and in Appendix D from [47] for CRDSA. To mitigate this limitation, the optimal configuration for CRDSA is with $N_{rep} = 3$ as presented in Fig. 2.3. In ACRDA, slightly better performance can be already achieved with $N_{rep} = 2$, thus reducing the demodulator complexity. It shall be recalled that ACRDA also reduces earth station complexity, as it does not require any control loop to keep time slot synchronization with the hub. Similarly to CRDSA, ACRDA performance improves in front of power imbalance. Fig. 8 from [61] shows that ACRDA with FEC $\rho = 1/3$, $N_{rep} = 2$ and power imbalance following a lognormal power distribution with standard deviation $\sigma = 3$ dB, can achieve a throughput $T = 1.5$ bits/symbol for a target $PLR < 10^{-3}$.

In Sect. IV from [61], Guray Acar and Eloi Garrido analyze and compare the delay performance between ACRDA and CRDSA. Results show that ACRDA reduces the delay by a factor of 10 compared to CRDSA for low loads (e.g. $G =$ 0.3 bits/symbol) and a factor of 2 at high loads (e.g. $G = 0.9$ bits/symbol).

In Fig. 2.9, the performance of ACRDA is compared against E-SSA. As we can see, in particular for the case of large power imbalance, E-SSA performance is better than ACRDA. The use of QPSK in ACRDA improves the efficiency, but also increases the sensitivity to channel estimation errors. Besides, as we have seen in Fig. 1.6, spread-spectrum achieves a higher aggregation of traffic with lower interference fluctuations which is favorable for RA.

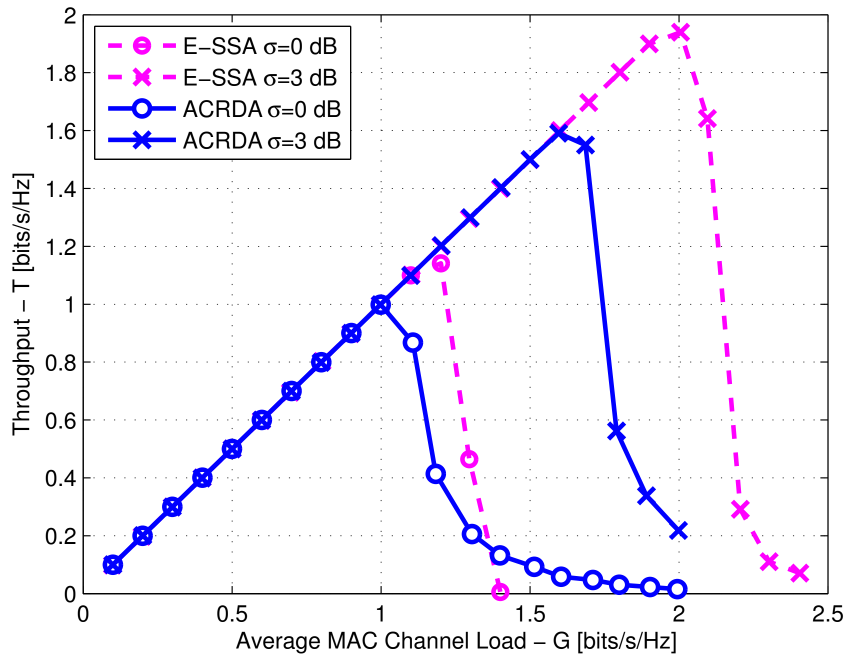


(a) Throughput

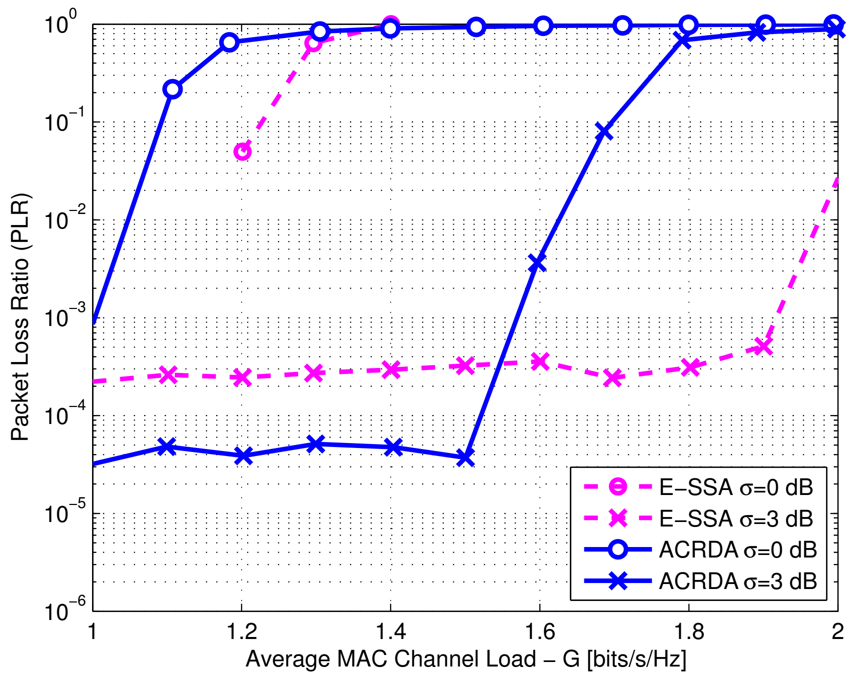


(b) PLR

Figure 2.8: Simulation and analytical ACRDA and CRDSA performance for $N_{\text{rep}} = 2$, N_{slots}=100 (simulations), QPSK modulation, 3GPP FEC $\rho = 1/3$, packet block size 100 bits, $E_s/N_0 = 10$ dB in the presence of no packets power imbalance and Poisson traffic, window size $W = 3$ virtual frames and a window step $\Delta W = 0.15$ [61].



(a) Throughput



(b) PLR

Figure 2.9: Simulated E-SSA performance with BPSK modulation, 3GPP FEC ρ=1/3, packet block size 100 bits, spreading factor 256 vs. ACRDA performance for $N_{rep} = 2$, N_{slots}=100, QPSK modulation, 3GPP FEC ρ=1/3, packet block size 100 bits, $E_s/N_0 = 10$ dB, window size W = 3 virtual frames and a window step ΔW = 0.15, with and without power imbalance and Poisson traffic.

Chapter 3

Outcomes

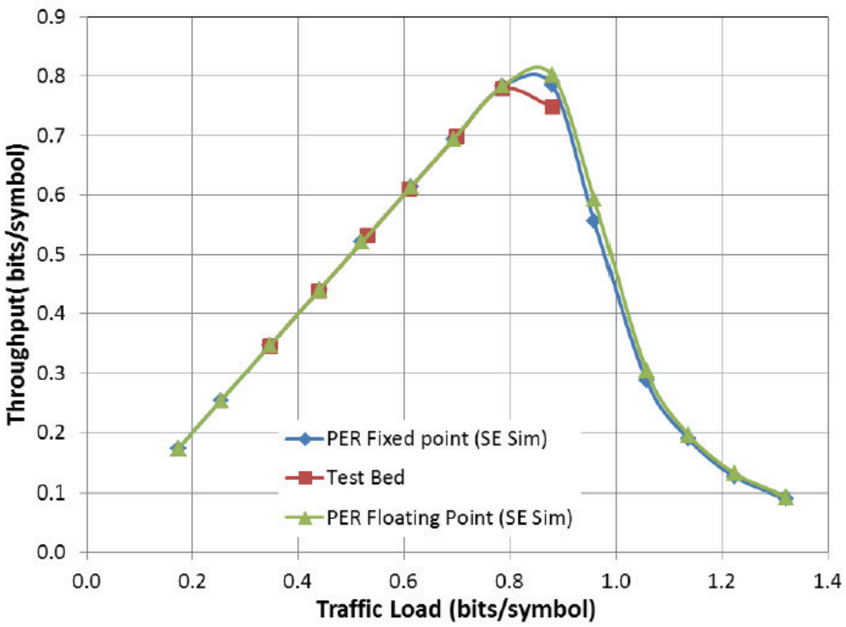
The contributions from the author in this PhD thesis have derived in a number of prototyping activities, commercial products and telecommunications standards. They are briefly presented in this chapter.

3.1 Prototypes

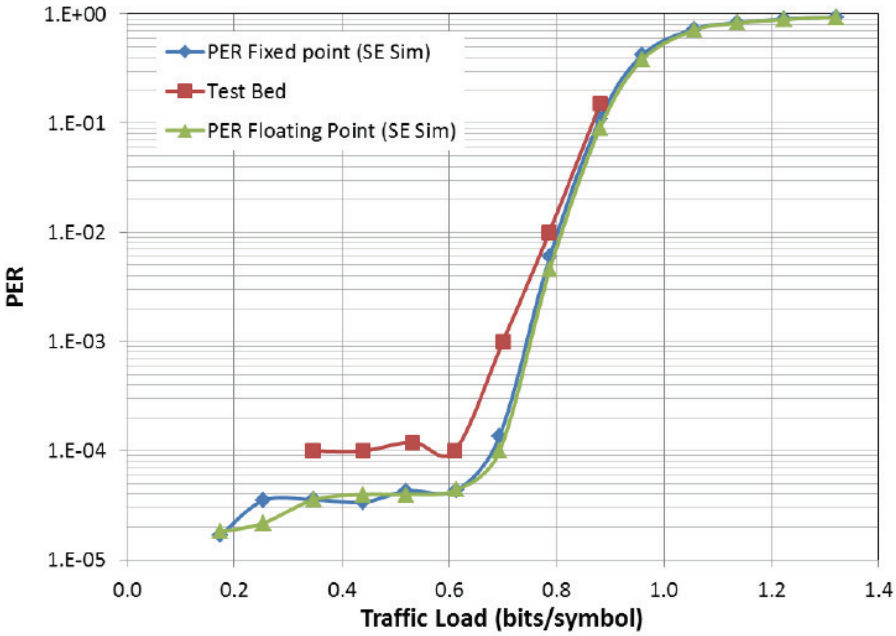
A real-time prototype of a CRDSA modulator and demodulator has been developed by Space Engineering (Italy) in 2011 in the frame of an ESA contract [63, 64]. Fig. 3.1 compares the measured results in the test bed against those obtained by simulations. We can see that experimental results are very close to the simulation findings assuming an ideal CRDSA demodulator.

A reference implementation of the E-SSA technique based on a software defined radio (SDR) platform was developed by MBI (Italy) in 2012 under Eutelsat's specifications [65, 66, 67]. The MBI prototype allowed to fully verify the E-SSA performance in a real-time environment including preamble detection, channel estimation, interference cancellation and frequency errors. We can see in Fig. 3.2 that the measured performance are very close to the simulated ones. The PLR remains very low until almost the peak MAC throughput and, as expected, power imbalance improves the E-SSA performance.

A second E-SSA prototype was developed in 2014 in the frame of an ESA project, called ANTARES [68], aiming at the development of a new purpose-built satellite communications system, including low-cost airborne terminals and a new open satellite communication protocol for Air Traffic Management (ATM). The new proposed communication protocol is based on E-SSA in the the return link (aircraft to hub) and is implemented in 200 kHz channels in L-band (1-2 GHz) with a chip rate of 160 kchip/s and a spreading factor $SF = 16$ or 4 [69, 70]. The performance of the new proposed telecommunication protocol have been verified means of an end-to-end Verification Test Bed (see Fig. 3.3). Laboratory measurements with the verification testbed confirm that a throughput above 1 bit/chip can be achieved with spreading factor $SF = 16$ (see Fig. 3.4) in the aeronautical channel with a target $PLR = 10^{-3}$. Slightly lower spectral efficiency, around 0.8 bits/s/Hz, is achieved with $SF = 4$ (see Fig. 3.5).



(a) Throughput



(b) PLR

Figure 3.1: Laboratory vs simulation results for CRDSA for $N_{\text{rep}} = 4$, N_{slots}=66, QPSK modulation, 3GPP FEC $\rho = 1/2$, symbol rate $R_s = 128$ ksymbols/s, packet block size 488 bits, $E_s/N_0 = 10$ dB in the presence of lognormal packets power unbalance with mean $\mu = 0$ dB, standard deviation $\sigma = 2$ dB.

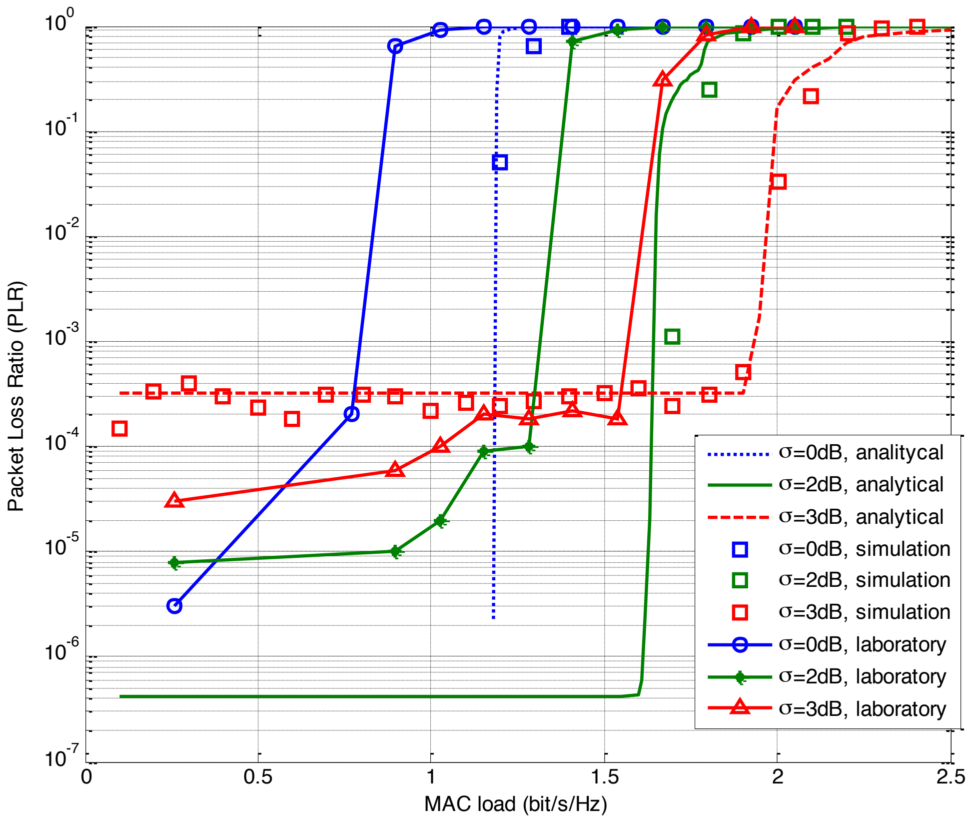


Figure 3.2: PLR vs. MAC loads and diffrent values of power imbalance standard deviation (C/N=-16 dB) [65].

It is also important to highlight the very good match between simulation and measurement results.

An ACRDA prototype is currently under development by DLR (Germany) under the frame of an ESA contract [71]. Measurement results will be available in 2016.

In chapter 2 from [72], Riccardo de Gaundezi and Gennaro Gallinaro compare the simulated CRDSA and E-SSA aggregated throughput versus the unconstrained and constrained in the used code rate and modulation. The simulated CRDSA throughput with 3 replicas, a PLR=10^{-3}, QPSK modulation and 3GPP turbo code with 100 bits block size is compared to the unconstrained and QPSK with FEC 100 bit block size constrained capacity bounds. In case of CRDSA the packets have been using a uniform in dB random packet power distribution with a maximum value of E_b/N_0 of 6, 9, 12 and 20 dB respectively. It can be observed that the simulated CRDSA throughput is quite close to the modulation and FEC constrained capacity at medium values of E_b/N_0. The distance is increasing for large values of E_b/N_0 possibly due to the fixed modulation format (QPSK) and code rate (1/3) adopted for CRDSA. For E-SSA, with an average SNR after de-spreading of 10 dB and using a uniform in dB random packet power distribution with a range of 6 dB, an unconstrained capacity bound of 2.5 bits/s/Hz and a constrained capacity bound with BPSK, spreading factor $SF = 16$ and FEC coding rate $\rho = 1/3$ of 2 bits/s/Hz are derived. These results show that the simulated E-SSA aggregated throughput of 2 bit/s/Hz presented in Sect. 2.2.1 match the modulation and FEC constrained capacity.

3.2 Standards and Systems

In the last years, a number of satellite communication standards have been developed integrating the most recent RA techniques. In the broadband access domain, the second generation of the DVB-RCS standard for interactive satellite systems [73], has added CRDSA as an optional feature, which is particularly advantageous for the SCADA and consumer profiles.

In the mobile context, the inclusion of the low-latency profile in the DVB-SH standard for satellite services to handheld [74], enabled the possibility to add a return link (earth station to hub), which is enhancing the DVB-SH standard for the support of interactive services. The ETSI S-band Mobile Interactive Multimedia (S-MIM) standard [75, 65] has adopted the E-SSA technique for the asynchronous access.

The E-SSA RA technology is finding commercial application in the recently deployed Eutelsat Broadcast Interactive System (EBIS) (see Fig. 3.6). The core of the EBIS system is the Fixed Satellite Interactive Multimedia (F-SIM) protocol [76]. The F-SIM protocol is implemented by the *Smart LNB* [77] on the earth stations. The Smart LNB implements conventional DVB-S2 on the forward link (hub to earth station) [78] and a proprietary evolution of the S-MIM standard [75] in the return link (earth station to hub). The EBIS system is already deployed in Ka-band on Eutelsat Ka-Sat satellite, as well as in Ku-band on different Eutelsat satellites.

Figure 3.3: ANTARES communication standard verification testbed.

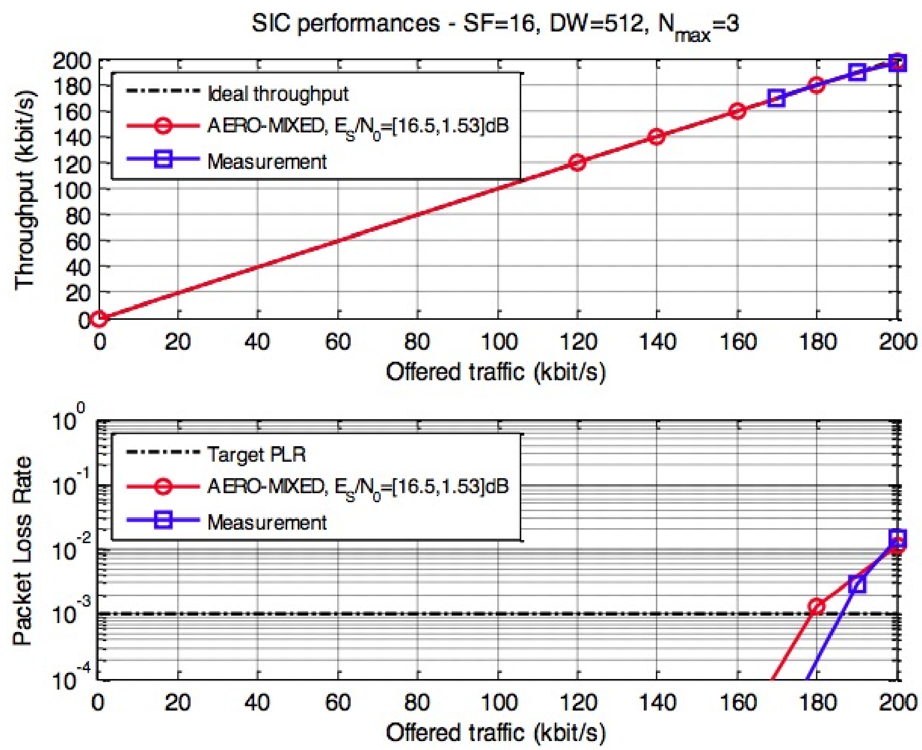


Figure 3.4: SIC performance for ANTARES communication protocol with chip rate $R_c = 160$ kchip/s, $SF = 16$, BPSK, code rate $\rho = 1/3$, data word 512 bits and 3 IC iterations.

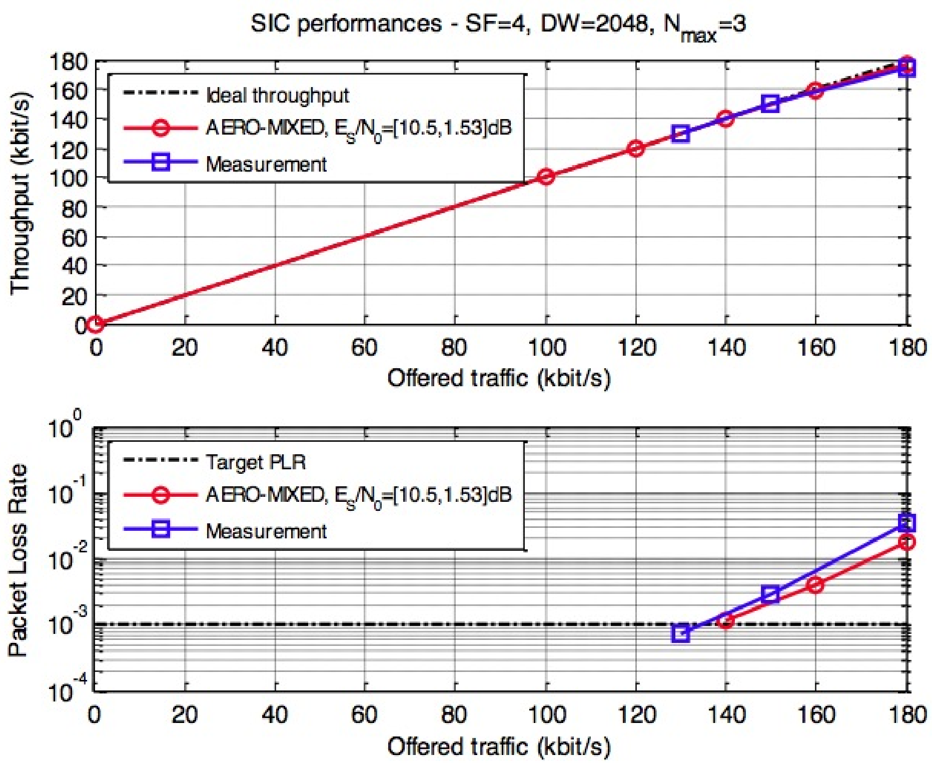


Figure 3.5: SIC performance for ANTARES communication protocol with chip rate $R_c = 160$ kchip/s, $SF = 4$, BPSK, code rate $\rho = 1/3$, data word 2048 bits and 3 IC iterations.

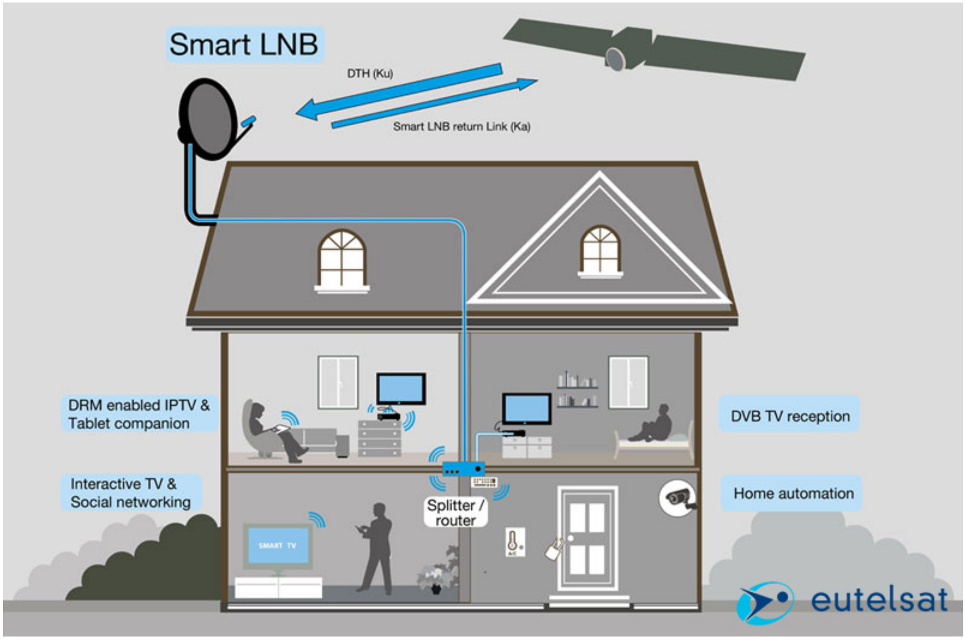


Figure 3.6: Eutelsat Broadcast Interactive System [76].

3.3 Example of a M2M satellite network

In this section, a realistic example of an M2M satellite network is described with the aim of describing the integration of the new proposed RA schemes with the upper layer protocols and to perform a preliminary system dimensioning exercise based on the traffic characteristics.

The selected scenario, is an aeronautical satellite network to track and monitor airplanes flying over oceanic airspace (e.g. over the Atlantic). The system uses the L-band (1-2 GHz) for radio links between the airplanes and the satellite, with an uplink frequency of 1.55 GHz (aircraft to satellite) and a downlink frequency of 1.65 GHz (satellite to aircraft). Frequency channels on uplink and downlink have a bandwidth of 200 kHz. Aircrafts are equipped with a low gain antenna and low power satellite communications terminal. A hub located on ground communicates with the satellite using a frequency band allocated to Fixed Satellite Services (e.g. in C, Ku or Ka-band). The satellite relays the signals received from the hub to the airplanes (forward link) as well as the signals received from the airplanes to the hub (return link). The hub is connected via a ground network to the to the Air Traffic Control (ATC) centre. A bidirectional communication link is established between the ATC centre and the airplanes. The network architecture is depicted in Fig. 3.7.

Airplanes transmit position reports periodically, and also triggered by an event on-board or upon request from the ATC centre. On average, a message is generated every 40 seconds per aircraft with an average length of 250 bytes, resulting in an average bit rate per aircraft of 50 bits/s. Headers from network

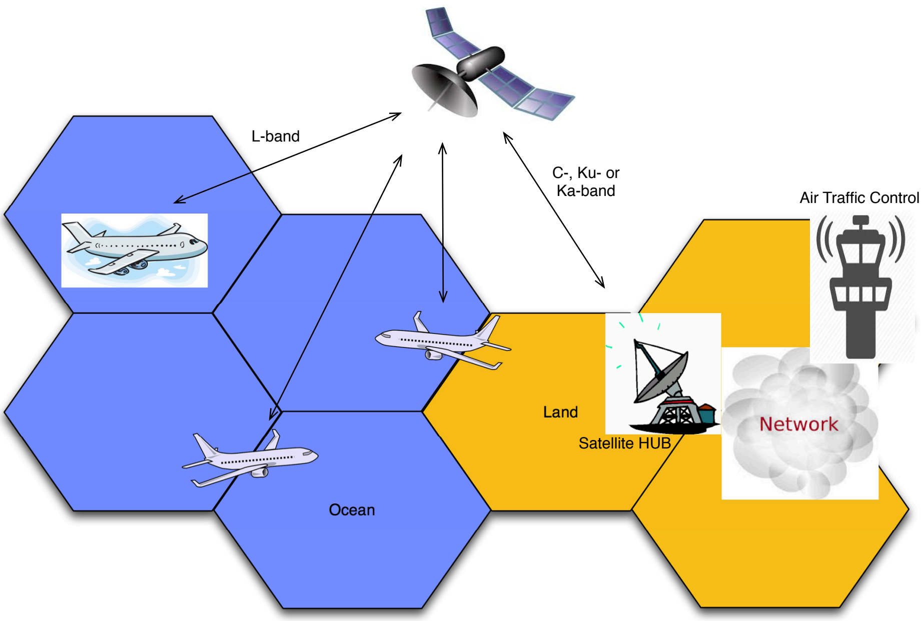


Figure 3.7: Aeronautical Satellite Network for Air Traffic Management.

protocols are compressed down to 4-7 bytes, e.g. using ROHC [79, 80], which allows an efficient use of bandwidth on low- and medium-speed links. At the link layer, the Generic Stream Encapsulation (GSE) protocol defined in [81] and adapted to the aeronautical environment in [69]. This encapsulation protocol is characterized by its flexibility and low overhead in the range of 3-4%. If we account for the compressed network headers and encapsulation overhead, the resulting average information bit rate per aircraft at physical layer is 54 bits/s.

We have seen in Sect. 3.1 that the ANTARES project proposes an air interface that can achieve spectral efficiencies in the return link above 1 bit/chip for a target $PLR = 10^{-3}$ by using the E-SSA technique. This means that in a 160 kchip/s channel (200 kHz bandwidth) we can track and monitor ≈ 3000 airplanes flying simultaneously over the oceanic airspace. Today, there are less of 3000 aircrafts flying over the Atlantic ocean over a whole day. At a bit rate of 3.3kbit/s per aircraft, the average transmission delay for each message will be 650ms, and the message will be received by the hub in less than 1s (if we account for the propagation delay). In total, the end-to-end message transmission delay from aircraft to Air Traffic Control centre will be < 1.5s, if we account for hub message decoding time and ground network delay from hub to satellite control centre.

These are remarkable performance results with a highly aggregated throughput, low PLR and low end-to-end delay, if we consider that a very large network population is sharing a communication channel with a very large propagation delay.

Part II

Contributions

Chapter 4

Contention Resolution Diversity Slotted Aloha (CRDSA): an Enhanced Random Access Scheme for Satellite Access Packet Networks

Chapter 5

Generalized Analytical Framework for the Performance Assessment of Slotted Random Access Protocols

Chapter 6

CRDSA patent: Method of packet mode digital communication over a transmission channel shared by a plurality of users

EP1686746 (B1), *Transmission de donnees par paquets a travers un canal de transmission partage par plusierus utilisateurs*
Inventors: E. Casini, O. del Rio Herrero, R. De Gaudenzi, D. M. E. Delaruelle, J.P. Choffray
Patent filed: 30 January 2006
Patent application publication: 2 August 2006
Patent published: 16 April 2008

US8094672 (B2), *Method of packet mode digital communication over a transmission channel shared by a plurality of users*
Inventors: E. Casini, O. del Rio Herrero, R. De Gaudenzi, D. M. E. Delaruelle, J.P. Choffray
Patent filed: 30 January 2006
Patent application publication: 3 August 2006
Patent published: 10 January 2012

(19) Europäisches Patentamt / European Patent Office / Office européen des brevets

(11) **EP 1 686 746 B1**

(12) **FASCICULE DE BREVET EUROPEEN**

(45) Date de publication et mention de la délivrance du brevet:
16.04.2008 Bulletin 2008/16

(51) Int Cl.:
H04L 12/56 *(2006.01)*

(21) Numéro de dépôt: **06290178.0**

(22) Date de dépôt: **30.01.2006**

(54) **Transmission de données par paquets à travers un canal de transmission partagé par plusieurs utilisateurs**

Paketedatenübertragung über einen gemeinsam genutzten Übertragungskanal

Packet data transmssion over a shared transmission channel

(84) Etats contractants désignés:
AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HU IE IS IT LI LT LU LV MC NL PL PT RO SE SI SK TR

(30) Priorité: **31.01.2005 FR 0500934**

(43) Date de publication de la demande:
02.08.2006 Bulletin 2006/31

(73) Titulaire: **AGENCE SPATIALE EUROPEENNE**
F-75738 Paris Cedex 15 (FR)

(72) Inventeurs:
- **Casini, Enrico**
  2317 BD Leiden (NL)
- **Del Rio Herrero, Oscar**
  2314 GD Leiden (NL)
- **De Gaudenzi, Riccardo**
  2313 ER Leiden (NL)
- **Delaruelle, Daniel Maurice Eliane**
  9100 Sint-Niklaas (BE)
- **Choffray, Jean-Pierre Georges Joseph Ghislain**
  6671 Bovigny (BE)

(74) Mandataire: **Jacquard, Philippe Jean-Luc et al**
Cabinet ORES
36, rue de St Pétersbourg
75008 Paris (FR)

(56) Documents cités:
WO-A-01/17171
GB-A- 2 309 849
US-A1- 2002 089 959

- **DILLON D: "Differentiated quality of service slotted ALOHA" COMPUTER COMMUNICATIONS AND NETWORKS, 2004. ICCCN 2004. PROCEEDINGS. 13TH INTERNATIONAL CONFERENCE ON CHICAGO, IL, USA 11-13 OCT. 2004, PISCATAWAY, NJ, USA,IEEE, 11 octobre 2004 (2004-10-11), pages 343-346, XP010774541 ISBN: 0-7803-8814-3**

EP 1 686 746 B1

Printed by Jouve, 75001 PARIS (FR)

US008094672B2

(12) **United States Patent**
Casini et al.

(10) **Patent No.: US 8,094,672 B2**
(45) **Date of Patent: Jan. 10, 2012**

(54) **METHOD OF PACKET MODE DIGITAL COMMUNICATION OVER A TRANSMISSION CHANNEL SHARED BY A PLURALITY OF USERS**

(75) Inventors: **Enrico Casini**, Leiden (NL); **Oscar Del Rio Herrero**, Leiden (NL); **Riccardo De Gaudenzi**, Leiden (NL); **Daniel Maurice Eliane Delaruelle**, Sint-Niklaas (BE); **Jean-Pierre Georges Joseph Ghislain Choffray**, Bovigny (BE)

(73) Assignee: **Agence Spatiale Europeenne** (FR)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1628 days.

(21) Appl. No.: **11/342,980**

(22) Filed: **Jan. 30, 2006**

(65) **Prior Publication Data**

US 2006/0171418 A1 Aug. 3, 2006

(30) **Foreign Application Priority Data**

Jan. 31, 2005 (FR) 05 00934

(51) **Int. Cl.**
H04W 4/00 (2009.01)
H04J 4/00 (2006.01)
H04L 12/413 (2006.01)

(52) **U.S. Cl.** **370/447**; 370/330; 370/436; 370/478

(58) **Field of Classification Search** 370/447, 370/330, 436, 478

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,434,847	A *	7/1995	Kou	370/252
5,768,254	A *	6/1998	Papadopoulos et al.	370/201
6,643,275	B1 *	11/2003	Gustafsson et al.	370/328
6,697,855	B1 *	2/2004	Le Dantec et al.	709/223
2002/0089959	A1	7/2002	Fischer et al.	
2002/0167920	A1 *	11/2002	Miyazaki et al.	370/329
2002/0191560	A1 *	12/2002	Chen et al.	370/331
2002/0196748	A1 *	12/2002	De Mier	370/310
2003/0027580	A1 *	2/2003	Goodjohn et al.	455/453
2003/0174663	A1 *	9/2003	Dillon	370/316
2004/0008726	A1 *	1/2004	Kelly et al.	370/468
2005/0013249	A1 *	1/2005	Kong et al.	370/235
2005/0249114	A1 *	11/2005	Mangin et al.	370/229
2006/0085551	A1 *	4/2006	Xie et al.	709/231

FOREIGN PATENT DOCUMENTS

WO WO 01/17171 A 3/2001

OTHER PUBLICATIONS

Dillon D., "Differentiated quality of service slotted ALOHA" *Computer Communications and Networks*, 2004, pp. 343-346.

International Search Report.

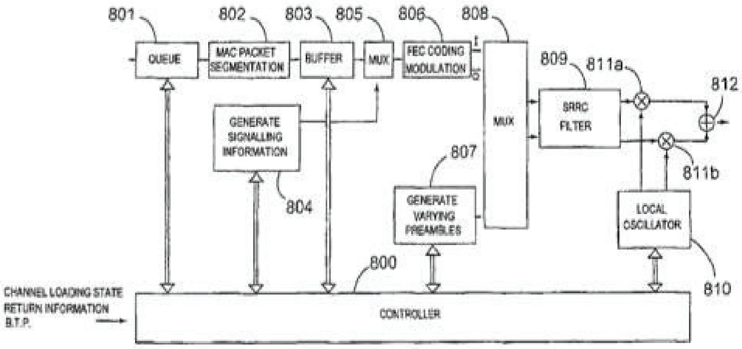
* cited by examiner

Primary Examiner — Ricky Ngo
Assistant Examiner — Paul Masur
(74) *Attorney, Agent, or Firm* — Alston & Bird LLP

(57) **ABSTRACT**

A first aspect of the invention is a method of transmitting data packets over a transmission channel shared by a plurality of users, based on the time and/or frequency diversity slotted Aloha technique, in which at least two replicas of each packet to be transmitted are sent over said transmission channel, wherein each replica transports signaling information enabling the other replica(s) of the same packet to be located in the time and/or frequency domain. A second aspect of the invention is a method of recovering packets in the receiver, the method exploiting said signaling information to execute an interference cancellation algorithm for recovering packets corrupted by collisions caused by access conflicts. Other aspects of the invention are a transmitter equipment and a receiver packet recovery equipment adapted to use said methods.

30 Claims, 18 Drawing Sheets



Chapter 7

High Efficiency Satellite Multiple Access Scheme for Machine-to-Machine Communications

Chapter 8

E-SSA patent: Methods, apparatuses and system for asynchronous spread-spectrum communication

EP2159926 (A1), *Methods, apparatuses and system for asynchronous spread-spectrum communication*
Inventors: O. del Rio Herrero, R. De Gaudenzi
Patent filed: 26 August 2008
Patent application publication: 3 March 2010

US7990874 (B2), *Methods, apparatuses and system for asynchronous spread-spectrum communication*
Inventors: O. del Rio Herrero, R. De Gaudenzi
Patent filed: 25 August 2009
Patent application publication: 4 March 2010
Patent published: 2 August 2011

(19) Europäisches Patentamt / European Patent Office / Office européen des brevets

(11) EP 2 159 926 A1

(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication:
03.03.2010 Bulletin 2010/09

(51) Int Cl.:
H04B 1/707 ***(2006.01)*** ***H04B 7/185*** ***(2006.01)***

(21) Application number: **08290801.3**

(22) Date of filing: **26.08.2008**

(84) Designated Contracting States:
AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MT NL NO PL PT RO SE SI SK TR
Designated Extension States:
AL BA MK RS

(71) Applicant: **AGENCE SPATIALE EUROPEENNE**
75735 Paris (FR)

(72) Inventors:
- **del Rio Herrero, Oscar**
2314 GD, LEIDEN (NL)
- **De Gaudenzi, Riccardo**
2587GL Den Haag (NL)

(74) Representative: **Priori, Enrico et al**
Cabinet Orès
36, rue de St. Pétersbourg
75008 Paris (FR)

Remarks:
Amended claims in accordance with Rule 137(2) EPC.

(54) **Methods, apparatuses and system for asynchronous spread-spectrum communication**

(57) A method of receiving data packets asynchronously transmitted by a plurality of user terminals using a spread-spectrum medium access protocol, comprising a step of cancelling interferences between colliding packets according to an innovative "sliding window" processing algorithm.

A gateway receiver adapted for carrying out interference cancellation according to said algorithm.

A method for controlling asynchronous packet transmission from a user terminal, comprising estimating a parameter indicative of the quality of information transmission through a communication channel; and inhibiting or allowing data transmission depending on a comparison between said estimated parameter and an adaptively varying threshold.

A user terminal comprising transmission control means adapted for carrying out such a method.

A communication system comprising a plurality of mobile user terminal communicating with a gateway through a satellite channel using an asynchronous spread-spectrum medium access protocol without closed-loop power control, wherein said user terminals and said gateway are of the kind described above.

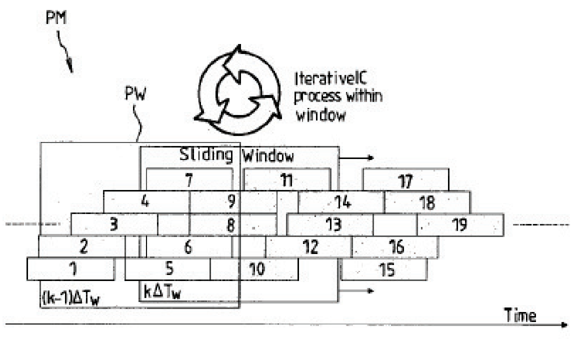


FIG.2

EP 2 159 926 A1

Printed by Jouve, 75001 PARIS (FR)

US007990874B2

(12) **United States Patent**
del Rio Herrero et al.

(10) **Patent No.: US 7,990,874 B2**
(45) **Date of Patent: Aug. 2, 2011**

(54) **METHODS, APPARATUSES AND SYSTEM FOR ASYNCHRONOUS SPREAD-SPECTRUM COMMUNICATION**

(75) Inventors: **Oscar del Rio Herrero**, Leiden (NL); **Riccardo De Gaudenzi**, Den Haag (NL)

(73) Assignee: **Agence Spatiale Europeenne**, Paris (FR)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 162 days.

(21) Appl. No.: **12/547,092**

(22) Filed: **Aug. 25, 2009**

(65) **Prior Publication Data**

US 2010/0054131 A1 Mar. 4, 2010

(30) **Foreign Application Priority Data**

Aug. 26, 2008 (EP) 08290801

(51) **Int. Cl.**
H04L 12/26 (2006.01)

(52) **U.S. Cl.** **370/236**; 370/517

(58) **Field of Classification Search** 370/517, 370/537, 487, 486, 347, 522
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,559,808	A	*	9/1996	Kostreski et al.	370/517
5,666,365	A	*	9/1997	Kostreski	370/486
5,729,549	A	*	3/1998	Kostreski et al.	370/522
5,748,683	A	*	5/1998	Smith et al.	375/347
5,809,059	A		9/1998	Souissi et al.	
5,822,324	A	*	10/1998	Kostresti et al.	370/487
5,852,612	A	*	12/1998	Kostreski et al.	370/537

FOREIGN PATENT DOCUMENTS

EP	1 686 746	8/2006
GB	2 406 479	3/2005
WO	WO 99/39445	8/1999
WO	WO 02/33838	4/2002
WO	WO 2007/051111	5/2007

OTHER PUBLICATIONS

International Search Report from European Application No. 08290801.3, filed Aug. 26, 2008.

Tadokoro Y et al.: "A new packet detection scheme in CDMA unslotted ALOHA system with successive interference cancellation"; GLOBECOM'01. 2001 IEEE Global Telecommunications Conference; San Antonio, TX; Nov. 25-29, 2001; New York, NY; IEEE, US; vol. 5, pp. 3173-3177; XP010747526.

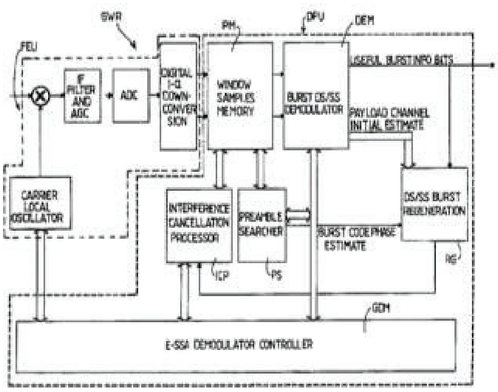
(Continued)

Primary Examiner — Thong Vu
(74) *Attorney, Agent, or Firm* — Alston & Bird LLP

(57) **ABSTRACT**

A method of receiving data packets asynchronously transmitted by a plurality of user terminals using a spread-spectrum medium access protocol, comprises a step of cancelling interferences between colliding packets according to an innovative "sliding window" processing algorithm. A gateway receiver is adapted for carrying out interference cancellation using this algorithm. Asynchronous packet transmission from a user terminal is controlled by estimating a parameter indicative of the quality of information transmission through a communication channel; and inhibiting or allowing data transmission depending on a comparison between said estimated parameter and an adaptively varying threshold. A user terminal comprises transmission control means adapted for carrying out such a method. A communication system comprises a plurality of mobile user terminal communicating with a gateway through a satellite channel using an asynchronous spread-spectrum medium access protocol without closed-loop power control, wherein the user terminals and said gateway are of the kind described above.

22 Claims, 18 Drawing Sheets



Chapter 9

Asynchronous Contention Resolution Diversity ALOHA: Making CRDSA Truly Asynchronous

Chapter 10

ACRDA patent: Method and apparatus for transmitting data packets over a transmission channel shared by a plurality of users

WO2015000518 (A1), *Method and apparatus for transmitting data packets over a transmission channel shared by a plurality of users*
Inventors: R. De Gaudenzi, O. del Rio Herrero
Patent filed: 3 July 2013
Patent application publication: 8 January 2015

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
8 January 2015 (08.01.2015)

WIPO | PCT

(10) International Publication Number
WO 2015/000518 A1

(51) International Patent Classification:
H04W 74/08 (2009.01) *H04L 1/00* (2006.01)
H04B 7/212 (2006.01)

(21) International Application Number:
PCT/EP2013/064082

(22) International Filing Date:
3 July 2013 (03.07.2013)

(25) Filing Language: English

(26) Publication Language: English

(71) Applicant: **ESA EUROPEAN SPACE AGENCY** [FR/FR]; 8-10 rue Mario Nikis, F-75738 Paris Cedex 15 (FR).

(72) Inventors: **DE GAUDENZI, Riccardo**; Leuvensestraat 106, NL-2587 GL Den Haag (NL). **DEL RIO HERRERO, Oscar**; Willem Dreeslaan 6, NL-2314 GD Leiden (NL).

(74) Agent: **MERH-IP MATIAS ERNY REICHL HOFFMANN**; Paul-Heyse-Str. 29, 80336 Munich (DE).

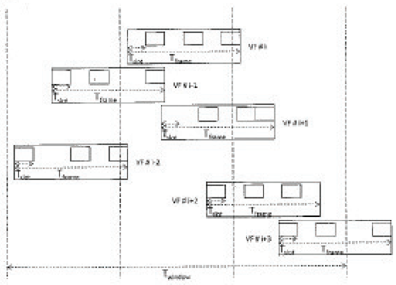
(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report (Art. 21(3))*

(54) **Title**: METHOD AND APPARATUS FOR TRANSMITTING DATA PACKETS OVER A TRANSMISSION CHANNEL SHARED BY A PLURALITY OF USERS

FIG. 6A



(57) **Abstract**: The invention relates to a method of transmitting data packets over a transmission channel shared by a plurality of transmitters, wherein transmission proceeds on the basis of a first unit of transmission of fixed length (virtual frame) that is subdivided into a plurality of second units of transmission of fixed length (time slots), the method comprising: associating, at a first transmitter, for each packet to be transmitted at least two replicas of the packet with respective second units of transmission within a current first unit of transmission; generating, at the first transmitter, the at least two replicas, wherein in each of the at least two replicas signaling information is included, the signaling information indicating relative positions of the other replicas of the same packet within the current first unit of transmission with respect to the given replica; setting, at the first transmitter, a start timing for beginning transmission of the current first unit of transmission independently of the other transmitters of the plurality of transmitters sharing the transmission channel; and transmitting the at least two replicas at respective timings in accordance with their association with the respective second units of transmission within the current first unit of transmission. The invention further relates to a method for demodulating a signal generated by the method of transmitting data packets.

WO 2015/000518 A1

Part III

Concluding remarks

Chapter 11

Conclusions

This thesis has presented three novel random access techniques that offer an excellent performance over the satellite environment and are well suited to the type of applications and services that have been recently emerging (e.g. consumer broadband access, interactive TV, machine-to-machine communications, transaction and safety of life communications). The first RA technique, CRDSA, is suited for slotted access (e.g. TDMA or MF-TDMA) that is typically used in broadband access networks. The second and third techniques, E-SSA and ACRDA, are fully asynchronous and are better suited for low cost fixed and mobile satellite messaging systems. The main difference between E-SSA and ACRDA is that E-SSA is a spread spectrum based RA technique. The three techniques have been analyzed in depth in this thesis, covering a description of the techniques, their key features, the processing at the transmitter and receiver sides, together with implementation aspects.

The new RA techniques can achieve an aggregated throughput above 1 bit/s/Hz for a $PLR < 10^{-3}$, which is typically required in data communications for an efficient performance of the upper layers network protocols. This represents a major performance improvement compared to known RA techniques currently used by satellite communication systems such as S-ALOHA (factor 1000), DSA (factor 50) and SSA (factor 2). The performance of the new schemes is further boosted in the presence of packets power imbalance at the receiver side, which is typically present in the satellite communications channel if no closed loop power control mechanisms are implemented. CRDSA and ACRDA can achieve a throughout in the order of 1.4 and 1.5 bit/s/Hz respectively in the presence of power imbalance. Particularly remarkable is the performance of E-SSA in front of power imbalance, which can achieve a throughput of 2 bit/s/Hz for a $PLR < 10^{-3}$. Power imbalance is not only beneficial for the performance of the novel RA schemes presented in this thesis, but also reduces complexity eliminating the need for closed loop power control schemes. On the contrary, the performance improvement of S-ALOHA and DSA in the presence of power imbalance is rather limited (power capture effect), and highly destructive for SSA (i.e. throughput reduction from 0.5 down to 0.02 bits/s/Hz for a target $PLR < 10^{-3}$). By comparing the performance improvement of E-SSA vs. SSA in front of power imbalance we get a factor 100. In terms of delay, E-SSA and ACRDA achieve similar delays to conventional RA schemes, while CRDSA introduces a higher delay due to the framed nature of the scheme (i.e. all packet replicas have to be transmitted within a common frame, and therefore, the earth station has to wait until the start of the next RA frame to transmit all packet replicas). As result, reducing the frame duration is desirable in CRDSA.

The presented RA schemes use iterative interference cancelation at the hub demodulator to resolve the collisions. To achieve high throughput with high reliability in RA, several design aspects at system, physical and MAC layer have been considered altogether. The performance of RA schemes exploiting IC are particularly sensitive to the choice of a number of aspects such as the number of replicas for each packet (CRDSA, ACRDA), number of CDMA codes (E-SSA), the channel coding rate, the FEC code performance at low SNR and, in the presence of colliding packets, the packets power imbalance received at the hub and the packet detection and channel estimation performances.

This thesis, has performed detailed analyses and simulations for the most important design parameters. CRDSA best performance is achieved when 3 replicas are used and a channel coding rate $\rho = 1/3$. The use of 3 replicas, as opposed to 2, helps eliminating the "loop" problem present in CRDSA and the coding rate $\rho = 1/3$ as opposed to 1/2 allows to successfully decode a packet even in the presence of one collision which helps in triggering the iterative IC process at the demodulator. A random access frame with more than 64 slots and 5 IC iterations are typically required to achieve good performance. On the physical layer side, one important aspect in CRDSA is channel estimation performance. This is done in a two step approach, with a first detection on the burst preamble for packet decoding, and once the packet bits have been successfully decoded, a second data aided channel estimation using also the payload symbols. It has been shown that this second step data aided channel estimation achieves IC results very close to ideal channel estimation.

For E-SSA, important design parameters are the sliding window size, the channel coding rate, the spreading factor, the number of CDMA codes, the number of IC iterations and the packet detection and channel estimation performances. It has been shown that a window size $W = 3$ packets gives good performance, as it covers the span of the interfering packets over the packet being decoded. Low coding rates are important in RA as we need to decode packets at very low SNIR in order to trigger the iterative IC process. It has been shown that FEC codes with rate $\rho = 1/3$ and small packets sizes (e.g. 100 information bits) have reasonable FER performance with $E_b/N_0 = -0.5$ dB. It has been shown that the spreading factor drives the level of traffic aggregation, which is higher when large spreading factors are used (e.g. $SF = 256$). It has been shown that with large spreading factors the interference level is almost constant over the whole packet duration and can be approximated as AWGN. The code collision probabilities has been analyzed in a fully asynchronous scenario and shown that 1 code is sufficient to achieve code collision probabilities well below the target $PLR < 10^{-3}$. Regarding the number of IC iterations, it has been shown that only 3 IC iterations are required at each sliding window position to get the best performance. Packet detection is a key aspect in E-SSA, as we need to operate in front of very high interference levels (e.g. $E_c/(N_0 + I_0) \simeq -30$ dB). Results obtained show that a preamble length of 128 symbols can achieve a probability of miss detection and false alarm below 10^{-3}. Channel estimation is performed in two steps as for CRDSA yielding a very good IC efficiency close to ideal channel estimation.

The optimal design parameters for ACRDA are similar to those of CRDSA and E-SSA, as this technique combines elements from them. It is important to remark, that in ACRDA the optimal number of replicas is 2 instead of 3 as found for CRDSA. Due to the asynchronous nature of the ACRDA scheme, the probability of loops is highly reduced already with two replicas, and there is no need to increase further complexity at the demodulator with one additional replica. The optimal sliding window size W is 3 virtual frames following the same rationale as for E-SSA.

This thesis has also presented novel analytical models to study the throughput and PLR performance of the new RA schemes. The proposed analytical model allows to predict the performance of the RA schemes in the presence of arbitrary FEC schemes, packet size, traffic and received packets power distributions. The model takes into account the fact that thanks to powerful physical layer coding, packets may be decoded with non zero probability also in the presence of collisions. The model also considers the effect of slot time diversity in case more than one packet replica is transmitted in the same frame, as it is the case for DSA. Two types of IC strategies have been modeled: successive interference cancellation over one slot position (CRDSA) or one window position (E-SSA and ACRDA), and iterative interference cancellation across the slots due to successful reception of packet replicas in other slots (CRDSA and ACRDA). The new model have been used to perform sensitivity analyses against a number of design parameters for the new RA schemes presented in this thesis, and to compare the performance improvement against conventional RA schemes. The good match between analytical and simulation results confirm the validity of the models, and make them extensible for future use in new or evolved RA schemes.

The new RA schemes have triggered the interest from industry who have developed real time laboratory prototypes [63, 67, 71] and validated the simulation results. In addition, CRDSA and E-SSA have been incorporated into two satellite telecommunication standards confirming the interest from industry [73, 75]. Finally, we conclude this thesis by mentioning that the E-SSA RA technology is finding commercial application in the recently deployed Eutelsat Broadcast Interactive System [76].

Chapter 12

Future work

The development of the new RA techniques presented in this thesis has opened up a new field of research. In this chapter some of the key open areas of research related to high performance satellite RA are listed.

The choice of the physical layer Forward Error Correcting (FEC) scheme for CRDSA is an important design driver. In CRDSA we are not operating in AWGN-like conditions, but in the presence of heavy co-channel interference the FEC collision resolution capability is important. Under these conditions of heavy multiple access interference, it is important to choose a FEC code that is able to recover a few packets and will then trigger the iterative IC process. Therefore, lower coding rates, although apparently reducing the individual packet bit rate, may be important to enhance the aggregated RA scheme performance. The final choice of coding rate is a tradeoff between increased overhead and RA performance improvement and has been preliminary studied in [60]. Regarding the FEC block size, it is preferable to have a small block size as this provides a smaller PLR in the lower signal-to-noise ratio (SNR) range [60]. Again, the reasoning is that successful detection of few packets under heavy co-channel interference conditions will be able to trigger the iterative IC process and eventually recover all packets from the RA frame. As a general rule, low coding rates ($\leq 1/2$) and small packet sizes (≤ 1000 bits) are recommended for CRDSA and in general, all RA schemes implementing IC.

Another interesting subject of research is related to reduction of the transmitter power consumption and cost. The use of constant envelope modulation like Continuous Phase Modulation (CPM) can bring several advantages, as it allows to replace the transmitter frequency up-conversion unit with a cheaper nonlinear frequency multiplier. Furthermore the use of CPM modulation allows to operate the transmitter amplifier in highly nonlinear mode with consequent reduction of the DC power requirements. Past work has shown the possibility to combine CPM with DS-SS [149]. Although CPM has been used in commercial S-ALOHA and SSA systems such as Sat3Play [150] and ArcLight [151], its use for iterative SIC based RA is still under investigation.

While for SSA and E-SSA the use of low-order modulation such as BPSK with low coding rate is close to optimum, recent investigations [152] indicate that for non-SS RA there may be some throughput advantage using modulation orders above QPSK when the SNR is above a certain value. Using QPSK in E-SSA does not bring any throughput advantage, but just an increase on the sensitivity to channel estimation phase errors. The use of a pilot in quadrature allows to have a continuous phase estimation which provides robustness in case of channels with phase noise and/or fading (mobile environment). However, concerning CRDSA, the use of QPSK instead of BPSK is related to the achievable spectral efficiency considering the TDMA type of access scheme. The idea is to use an energy efficient signaling scheme like QPSK (or a higher order modulation) with low rate FEC to minimize the power of the transmitter while getting very good aggregate RA throughput.

When the RA network allows to exploit the incoming packet power imbalance, this power distribution can be optimized to enhance the system throughput. While for E-SSA RA some semi-analytical optimization has been derived in [153], a similar effort for non spread spectrum RA is still undergoing. Initial findings indicate that also for CRDSA and ACRDA a uniform in dB incoming packet distribution can improve the throughput performance.

In systems with a high SNR, but reduced packet power dynamic range, MMSE preprocessing may be implemented to enhance the SNIR of the received signal before the signal demodulation. The MMSE detector can exploit the knowledge of the signal structure to compute the matrix filter. Preliminary analyses and simulation results on a newly proposed ME-SSA scheme can be found in [154].

A major drawback of TDMA is its high peak transmit power requirement resulting from the fact that each terminal is transmitting on a small fraction ($1/N_{slots}$) of the frame duration. Since the PLR of a system is directly related to the ratio between the bit energy and the noise floor level (i.e. the E_b/N_0), TDMA needs a (peak) power transmission N_{slots} times higher than FDMA or CDMA. In thin route satellite communications networks Multi-Frequency TDMA (MF-TDMA) was introduced to mitigate this problem. The multi-frequency concept can be easily applied to CRDSA or ACRDA leading to MF-CRDSA [58]. The peak power gain reduction as for MF-CRDSA will be proportional to the ratio of frequency to time slots of the system. Besides, using the frequency domain will reduce the RA frame duration thus reducing the end-to-end delay in CRDSA. The multi-frequency concept can be also applied in ACRDA to reduce the terminal peak power requirements.

The exploitation in ACRDA of techniques such as soft combining of packet replicas proposed in [140] or the combining of the best replica packets chunks to generate a better packet of interest as suggested in [143] or the Coded Slotted ALOHA soft combining scheme [136] represent potential area of future investigation.

Similarly one can consider the techniques proposed in [139], [140] to pseudo-randomize the slot positions as a function of the transmitted data to remove the replica signaling overhead. This is particularly interesting in case small packets have to be transmitted.

The issue of advanced Spread Spectrum RA demodulation in case of multi-beam satellite networks has been recently tackled in [155]. It has been shown that for a mobile multi-beam system exploiting the S-MIM standard further RA capacity gain can be achieved using full frequency reuse among the beams and joint beam processing at the gateway. In particular, two different multi-beam joint processing techniques have been investigated by simulation: basic (decoded packets are send to upper layers belonging to other beams) and enhanced cooperation (the decoded data is sent to the co-frequency demodulators on top the basic cooperation). The latter approach, although more complex to implement, brings extra gain on top of the basic cooperation. More work in this area is required to assess the practical feasibility and gains achievable exploiting joint beam processing.

In this thesis we have shown that RA alone can achieve throughput performance truly comparable with DAMA schemes with advantages in terms of transmission latency and signaling reduction. Furthermore, the presented advanced RA techniques are easily scalable to very large networks. However, there may be applications where the type of traffic can be both bursty or bulky. In this case the combination of high performance RA schemes with DAMA can represent the best solution to cope with this very time variant traffic conditions. More work is required to investigate the best way to adaptively switch from the new efficient and reliable RA to DAMA type of access schemes [144, 156].

Finally, the techniques presented in this thesis can also be adopted in terrestrial wireless networks to improve their performance in terms of capacity and energy consumption. Examples systems for application are Radio Frequency Identification (RFID) systems [139, 140] and M2M networks [157, 158].

Bibliography

[1] M. Williamson, *Spacecraft Technology: The Early Years*, The Institution of Engineering and Technology, 2006.

[2] K.M.S. Murthy, J. Alan, J. Barry, B.G. Evans, N. Miller, R. Mullinax, P. Noble, B. O'Neal, J.J. Sanchez, N. Seshagiri, D. Shanley, J. Stratigos, J.W. Warner, *VSAT user network examples*, IEEE Communications Magazine, Vol. 27, Issue 5, pp. 50-57, May 1989.

[3] B. Arbesser-Rastburg, R. Bellini, F. Coromina, R. De Gaudenzi, O. del Rio Herrero, M. Hollreiser, R. Rinaldo, P. Rinous, A. Roederer, *R&D directions for next generation broadband multimedia systems: an ESA perspective*, 20th AIAA International Communications Satellite Systems Conference (ICSSC), Montreal, Canada, May 13-15, 2002.

[4] Satellite Industry Association *State of Satellite Industry Report*, September 2014.

[5] Euroconsult, *High throughput satellites: on course for new horizons*, 2014 Edition.

[6] Northern Sky Research, *HTS Revenues to Overtake FSS in Battleground Applications*, http://www.nsr.com/news-resources/nsr-in-the-press/nsr-press-releases/hts-revenues-to-overtake-fss-in-battleground-applications/.

[7] Via Satellite, *The Continuing Momentum of M2M/IoT via Satellite*, http://www.satellitetoday.com/publications/2015/01/20/the-continuing-momentum-of-m2miot-via-satellite/.

[8] G. Maral, M. Bousquet, *Satellite Communicaitons Systems*, Fifth Edition, John Wiley & Sons Ltd, 2009.

[9] ETSI EN 300 421 Ver. 1.1.2, *Digital Video Broadcasting (DVB); Framing structure, channel coding and modulation for 11/12 GHz satellite services*, August 1997.

[10] ETSI EN 302 307-1 Ver. 1.4.1, *Digital Video Broadcasting (DVB); Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications; Part 1: DVB-S2*, November 2014.

[11] G. Maral, *VSAT Networks*, Second Edition, John Wiley & Sons Ltd, 2003.

[12] A.H. Rana, J.S. McCoskey, W.A. Check, *VSAT technology, trends, and applications*, Proceedings of the IEEE, Vol. 78, Issue 7, pp. 1087 - 1095, July 1990.

[13] D. Chakraborty, *VSAT Communications Networks - An overview*, IEEE Communications Magazine, Vol. 26, No. 5, pp. 10-24, May 1988.

[14] F.A. Tobagi, *Multiaccess Protocols in Packet Communication Systems*, IEEE Transactions on Communications, Vol. COM-28, No. 4, pp. 468-488, April 1980.

[15] C. Retnadhas, *Satellite Multiple Access Protocols*, IEEE Communications Magazine, Vol. 18, No. 5, pp. 16-20, September 1980.

[16] C.J. Wolejsza, D. Taylor, M. Grossman, W.P. Osborne, *Multiple Access Protocols for Data Communications via VSAT Networks*, IEEE Communications Magazine, Vol. 25, No. 7, July 1987.

[17] D. Raychaudhuri, K. Joseph, *Channel Access Protocols for Ku-band VSAT Networks: a comparative evaluation*, IEEE Communications Magazine, Vol. 26, No. 5, pp. 34-44, May 1988.

[18] H. Peyravi, *Medium Access Control Protocol Performance in Satellite Communications*, IEEE Communications Magazine, Vol. 37, No. 3, pp. 62-71, March 1999.

[19] P.M. Feldman, *An Overview and Comparison of Demand Assignment Multiple Access (DAMA) Concepts for Satellite Communications Networks*, RAND corporation, 1996.

[20] J.G. Puente, *A PCM-FDMA demand assignment satellite multiple access experiment*, AIAA 2nd Communications Satellite Systems Conference, paper No. 68-451, 8-10 April 1968, San Francisco (USA).

[21] G. Frenkel, *The grade of service in multiple-access satellite communications systems with demand assignments*, IEEE Transactions on Communications, Vol. 22, No. 10, pp. 1681-1685, October 1974.

[22] W.E. Leland, *On the self-similar nature of Ethernet traffic (Extended version)*, IEEE/ACM Transactions on Networking, Vol. 2, No. 1, February 1994.

[23] V. Paxson, S. Floyd, *Wide Area Traffic: the failure of Poisson modeling*, IEEE/ACM Transactions on Networking, Vol. 3, No. 3, June 1995.

[24] I. Jacobs, L.N. Lee, A. Viterbi, R. Binder, R. Bressler, N.T. Hsu, R. Weissler, *CPODA - A demand Assignment protocol for Satnet*, in Proceeding of the fifth symposium on data communications (SIGCOMM'77), pp. 2.5-2.9, 1977.

[25] T. Le-Ngoc, S.V. Krishnamurthy, *Performance of combined free/demand assignment multiple-access schemes in satellite communications*, Wiley International journal of satellite communications, Vol. 14, No. 1, pp. 11-21, January 1996.

[26] T. Le-Ngoc and I.M. Jahangir, *Performance analysis of CFDAMA-PB protocol for packet satellite communications*, IEEE Transactions on Communications, Vol. 46, No. 9, pp. 1206-1214, September 1998.

[27] O. del Río Herrero, G. Foti and G. Gallinaro, *Spread-spectrum techniques for the provision of packet access on the reverse link of next-generation broadband multimedia satellite systems*, IEEE Journal on Selected Areas in Communications, Vol. 22, Issue 3, pp. 574 - 583, April 2004

[28] Z. Jiang, Y. Li, V.C.M. Leung, *A Predictive Demand Assignment Multiple Access Protocol for Broadband Satellite Networks Supporting Internet Applications*, IEEE International Conference on Communications (ICC), pp. 2973 - 2977, Vol.5, 28 April - 2 May 2002, New York (USA)

[29] M. Hasegawa, G. Wu, M. Mizuno, *Applications of nonlinear prediction methods to the Internet traffic*, Proc. International Symposium on Circuits and Systems, vol. 3, pp. 169-172, May 2001, Sydney (Australia).

[30] H.W. Lee and J. W.Mark, *Combined random/reservation access for packet switched transmission over a satellite with on-board processing: Part I Global beam satellite*, IEEE Transactions on Communications, Vol. COM-31, No. 10, pp. 1161-1171, October 1983.

[31] D. M. Chitre, VSAT Networks: Architectures, Protocols, and Management, IEEE Communications Magazine, July 1988, Vol. 26, No. 7, pp. 28-38, July 1988.

[32] D. Bertsekas and R. Gallager, *Data Networks*, Second Edition, Prentice Hall, 1992.

[33] S. Keshav, *An Engineering Approach to Computer Networking*, Addison-Wesley Professional, 1997.

[34] L. Kleinrock and F.A. Tobagi, *Packet switching in radio channels: part I - Carrier sense multiple access modes and their throughput-delay characteristics*, IEEE Transactions on Communications, Vol. COM-23, No. 12, pp. 1400-1416, December 1975.

[35] R. M. Metcalfe and D.R. Boggs, *ETHERNET: Distributed packet switching for local computer networks*, Communications of the ACM magazine, Vol. 19, No. 7, pp. 395-404, July 1976.

[36] F.A. Tobagi and L. Kleinrock, *Packet Switching in Radio Channels: PartII - The Hidden Terminal Problem in Carrier Sense Multiple-Access and the Busy-Tone Solution*, IEEE Transactions on Communications, Vol. COM-23, No. 12, December 1975.

[37] IEEE Std 802.3-2005, *IEEE Standard for Information technology; Telecommunications and information exchange between systems local and metropolitan area networks; Specific requirements Part 3: Carrier sense multiple access with collision detection (CSMA/CD) access method and physical layer specifications*, December 2005.

[38] IEEE Std 802.11-2012, *IEEE Standard for Information technology; Telecommunications and information exchange between systems local and metropolitan area networks; Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, March 2012.

[39] P. Karn, *MACA - A New Channel Access Method for Packet Radio*, Proceedings of the ARRL/CRRL Amateur Radio 9th Computer Networking Conference, pp. 134-140, 22 September 1990, London and Ontario (Canada).

[40] V. Bharghavan, A. Demers, S. Shenker, L. Zhang, *MACAW: A Media Access Protocol for Wireless LAN's*, ACM SIGCOMM, 1994.

[41] C. Fullmer, J.J. Garcia-Luna-Aceves, *Floor Acquisition Multiple Access (FAMA) for packet radio networks*, Computer Communication Review, Vol. 25, No. 4, ACM SIGCOMM '95, Cambridge, MA, USA, 28 Aug.-1 Sept. 1995.

[42] 3GPP TS 25.214 v3.12.0, *Physical Layer Procedures (FDD); Release 1999*, March 2003.

[43] N. Abramson, *The ALOHA system - Another alternative for computer communications,* in 1970 Fall Joint Comput. Conf. AFIPS Conf. Proc., vol. 37, pp. 281-285, AFIPS Press, Montvale (NJ), 1970.

[44] N. Abramson, *The Throughput of Packet Broadcasting Channels*, IEEE Transactions on Communications, Vol. COM-25, No. 1, pp. 117-128, January 1977.

[45] L. G. Roberts, *ALOHA Packet Systems with and Without Slots and Capture*, Arpanet Satellite System Note 8 (NIC Document #11290), 26 Jun. 1972.

[46] G.L. Choudhury and S.S. Rappaport, *Diversity ALOHA - A Random Access Scheme for Satellite Communications*, IEEE Transactions on Communications, Vol. COM-31, pp. 450-457, March 1983.

[47] O. del Río Herrero and R. De Gaudenzi, *Generalized Analytical Framework for the Performance Assessment of Slotted Random Access Protocols*, IEEE Transactions on Wireless Communications, Vol. 13, No. 2, pp. 809-821, February 2014.

[48] N. Abramson, *Multiple Access in Wireless Digital Networks*, IEEE Proceedings, Vol. 82, No. 9, pp. 1360-1370, September 1994.

[49] C. Pateros, *Novel direct sequence spread spectrum multiple access technique,* in MILCOM 2000, 21st Century Military Communications Conference Proceedings, Vol. 2, pp. 564-568, Los Angeles (CA) Oct. 22-25, 2000.

[50] O. del Río Herrero and R. De Gaudenzi, *High Efficiency Satellite Multiple Access Scheme for Machine-to-Machine Communications*, IEEE Transactions on Aerospace and Electronic Systems, Vol. 48, No. 4, pp. 2961-2989, October 2012.

[51] ETSI EN 301 790 v1.5.1, *Digital Video Broadcasting (DVB); Interaction channel for satellite distribution systems*, May 2009.

[52] Telecommunication Industry Association TIA-1008-A, *IP Over Satellite*, May. 2006.

[53] S. Verdu, *Multiuser detection*, Cambridge Univ. Press, 1998.

[54] C. C. Lee, *Random signal levels for channel access in packet broadcast networks*, IEEE J. Select. Areas Commun., Vol. 5, No. 6, pp. 1026-1034, July 1987.

[55] I. Cidon, J. Kodesh and M. Sidi, em Erasure, capture, and random power level selection in multiple access systems, IEEE Transactions on Communications, Vol. 36, No. 3, pp. 263-271, March 1988.

[56] R. O. LaMaire, A. Krishna and M. Zorzi, *On the randomization of transmitter power levels to increase throughput in multiple access radio systems*, Journal Wireless Networks, Vol. 4, No. 3, pp. 263 - 277, March 1998, Kluwer Academic Publishers Hingham, MA (USA).

[57] E. Casini, R. De Gaudenzi, O. del Río Herrero, *Contention Resolution Diversity Slotted Aloha (CRDSA): an Enhanced Random Access Scheme for Satellite Access Packet Networks,* IEEE Transactions on Wireless Communications, Vol. 6, No. 4, pp. 1408-1419, Apr. 2007.

[58] E. Casini, O. del Río Herrero, R. De Gaudenzi, D.M.E. Delaruelle, J.P. Choffray, *Transmission de donnees par paquets a travers un canal de transmission partage par plusierus utilisateurs*, European Patent EP1686746 (B1), 30 January 2006.

[59] O. del Río Herrero, R. De Gaudenzi, *Methods, apparatuses and system for asynchronous spread-spectrum communications*, U.S. Patent 7,990,874 B2, August 2, 2011.

[60] O. del Río Herrero, R. De Gaudenzi, J. Pijoan Vidal, *Design Guidelines for Advanced Random Access Protocols*, 30st AIAA International Communications Satellite Systems Conference (ICSSC), 24-27 Sep. 2012, Ottawa (Canada).

[61] R. De Gaudenzi, O. del Río Herrero, G. Acar, E. Garrido Barrabés, *Asynchronous Contention Resolution Diversity Aloha: Making CRDSA Truly Asynchronous*, IEEE Transactions on Wireless Communications, Vol. 13, No. 11, pp. 6193-6206, November 2014.

[62] R. De Gaudenzi, O. del Río Herrero, *Method and apparatus for transmitting data packets over a transmission channel shared by a plurality of users*, World Intellectual Property Organization Patent WO2015000518 (A1), 3 July 2013.

[63] Space Engineering, *Advanced Modem Prototype for Interactive Satellite Terminals (AMPIST)*, ESA Contract No. 20668/07/NL/JD, https://artes.esa.int/advanced-modem-prototype-interactive-satellite-terminals-ampist

[64] R.Romanato, E. Rossini, G. Chiassarini, A. Masci, D. Silvi, P. Burzigotti, D. Giancristofaro, *AMPIST: An Advanced Modem Prototype For Interactive Satellite Terminals with Contention Resolution Diversity Slotted ALOHA (CRDSA) Capabilities*, in 17th Ka and Broadband Communications, Navigation and Earth Observation Conference, 3-5 October 2011, Palermo (Italy)

[65] S. Scalise, C.P. Niebla, R. De Gaudenzi, O. del Rio Herrero, D. Finocchiaro, A. Arcidiacono, *S-MIM: a novel radio interface for efficient messaging services over satellite*, IEEE Communications Magazine, Vol. 51 , No. 3, pp. 119-125, March 2013.

[66] F. Basile, G. Mendola, *Satellite Hub Communication System GPU Based*, GPU Technology Conference, 14-17 May 2012, San Jose (CA).

[67] M. Andreacci and G. Mendola, F. Collard, D. Finocchiaro, A. Recchia, *Enhanced spread spectrum ALOHA demodulator implementation, laboratory tests and satellite validation*, Wiley International Journal on Satellite Communications and Networking, Special Issue on S-band Mobile Interactive Multimedia, Vol. 32, No. 6, Page 521-533, November/December 2014.

[68] *AeroNauTicAl REsources Satellite based (ANTARES)*, ESA Contract 22851/09/NL/AD, https://artes.esa.int/projects/antares

[69] *ANTARES Communication Standard Technical Specifications*, https://artes.esa.int/news/iris-antares-study-updates-draft-satellite-communications-standard

[70] J. Batlle, I. Vega, J. Vila, D. Fernandez, L. Albiol, J.M. Cebrian, C. Ciancarelli, P. Burzigotti, *New satellite-based communication standard for Air Traffic Management*, in 19th Ka and Broadband Communications, Navigation and Earth Observation Conference and 31st AIAA International Communications Satellite Systems Conference (ICSSC), 14-17 October 2013, Florence (Italy).

[71] *Prototypes for Advanced Access Schemes*, ESA Contract 4000110938/14/NL/CLP, 2014.

[72] O. del Río Herrero, R. De Gaudenzi, G. Gallinaro, *High-performance random access schemes*, in Co-operative and cognitive satellite systems, S. Chatzinotas, B. Ottersten, R. De Gaudenzi, Ed. Academic Press, 2015, pp. 35-82.

[73] ETSI EN 301 542-2 v1.1.1, *Digital Video Broadcasting (DVB); Second Generation DVB Interactive Satellite System (DVB-RCS2); Part 2: Lower Layers for Satellite Standard*, January 2012.

[74] ETSI EN 302 583 v1.1.1, *Digital Video Broadcasting (DVB); Framing Structure, channel coding and modulation for Satellite Services to Handheld devices (SH) below 3 GHz*, March 2008.

[75] ETSI TS 102 721-3 v1.1.1, *Satellite Earth Stations and Systems; Air Interface for S-band Mobile Interactive Multimedia (S-MIM); Part 3: Physical Layer Specification, Return Link Asynchronous Access*, December 2011.

[76] A. Arcidiacono, D. Finocchiaro, F. Collard, S. Scalise, F. Lazaro Blasco, R. De Gaudenzi, S. Cioni, N. Alagha, M. Andrenacci, *From S-MIM to F-SIM: Making Satellite Interactivity Affordable at Ku and Ka-band*, Accepted for Publication in Wiley International Journal on Satellite Communications and Networking, special issue on Ka-band satellite communications, 2015.

[77] Eutelsat, *Eutelsats Smart LNB for Direct-to-Home antenna*, http://www.eutelsat.com/en/services/broadcast/direct-to-home/smart-LNB.html

[78] ETSI EN 302 207 v1.3.1, *Digital Video Broadcasting (DVB); Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications (DVB-S2)*, March 2013.

[79] IETF RFC 5795, *The RObust Header Compression (ROHC) Framework*, March 2010.

[80] IETF RFC 3095, *RObust Header Compression (ROHC): Framework and four profiles: RTP, UDP, ESP, and uncompressed*, July 2001.

[81] J. Cantillo, B. Collini-Nocker, U. De Bie, O. del Rio, G. Fairhurst, A. Jahn R. Rinaldo,*GSE: A Flexible, yet Efficient Encapsulation for IP over DVB-S2 Continuous Generic Streams*, International Journal of Satellite Communications and Networking (IJSCN), vol. 26, Issue 3, pp. 231-250, May/Jun. 2008.

[82] T. Le-Ngoc, and J.I. Mohammed, *Combined free/demand assignment multiple access (CFDAMA) protocols for packet satellite communications; Universal Personal Communications*, in *Conf. Rec. 2nd International Conference on Personal Communications*, 12-15 Oct. 1993, vol. 2, pp. 824 - 828.

[83] S. S. Lam, *A carrier sense multiple access protocol for local networks*, Computer Networks, vol. 4, pp. 21-32, 1980.

[84] D. Raychaudhuri, *Aloha with Multipacket Messages and ARQ-type Retransmission Protocols-Throughput Analysis*, IEEE Trans. on Comm., vol. COM-32, no. 2, pp. 148-154, Feb. 1984.

[85] D. Raychaudhuri, *Stability, Throughput, and Delay of Asynchronous Selective Reject Aloha*, IEEE Trans. on Comm., Vol. 35, No. 7, pp. 767-772, July 1987.

[86] European Telecommunication Standardisation Institute (ETSI) TR 101 790 V1.2.1, *Digital Video Broadcasting (DVB); Interaction channel for Satellite Distribution Systems; Guidelines for the use of EN 301 790*, January 2003.

[87] P. Patel, and J. Holtzman, *Analysis of a simple successive interference cancellation scheme in a DS/CDMA system*, IEEE Journal on Selected Areas in Comm., Vol. 12 , No. 5, pp. 796 - 807, June 1994.

[88] R. De Gaudenzi, F. Giannetti, and M. Luise, *Signal Recognition and Signature Code Acquisition in CDMA Receivers for Mobile Communications*, IEEE Transactions on Vehicular Tech., Vol. 47, No. 1, pp. 196 - 208, Feb. 1998.

[89] European Telecommunication Standardisation Institute (ETSI) TR 101 112 v3.2.0, *Universal Mobile Telecommunications System (UMTS); Selection procedures for the choice of radio transmission technologies of the UMTS*, April 1998.

[90] R. De Gaudenzi, O. del Río Herrero, *Advances in Random Access protocols for satellite networks*, International Workshop on Satellite and Space Communications (IWSSC), pp. 331-336, 9-11 September 2009, Siena (Italy).

[91] A.H. Abdelmonem, T.N. Saadawi, *Performance analysis of spread spectrum packet radio network with channel load sensing*, IEEE Journal on Selected Areas in Communications, Vol. 7, No. 1, January 1989, pp. 161-166.

[92] O. del Río Herrero, R. De Gaudenzi, *A High-Performance MAC Protocol for Consumer Broadband Satellite Systems*, Proceedings of 27th AIAA International Communications Satellite Systems Conference)ICSSC), 1-4 June 2009, Edinburgh (United Kingdom).

[93] K. S. Ghilousen, I. M. Jacobs, R. Padovani, A. J. Vitebi, L. A. Weaver, C. W. Wheatley III, *On the Capacity of a Cellular CDMA System*, IEEE Transactions on Vehicular Technology, Vol. 40. No. 2, pp. 303-312, May 1991.

[94] R. De Gaudenzi, F. Giannetti, *Analysis of an Advanced Satellite Digital Audio Broadcasting System and Complementary Terrestrial Gap-Filler Single Frequency Network*, IEEE Transactions on Vehicular Technology Vol. 42, No. 2, pp. 194-210, May 1994.

[95] P. Cardieri, T. S. Rappaport, *Statistics of the Sum of Lognormal Variables in Wireless Communications*, Vehicular Technology Conference 2000, Proceedings of the 51st Vehicular Technology Conference Spring, Volume: 3, pp. 1823-1827, May 2000, Tokyo (Japan).

[96] 3GPP TS 25.212 v3.11.0, *Multiplexing and channel coding (FDD); Release 1999*, September 2002.

[97] A. Giorgetti, M. Chiani, *Influence of Fading on the Gaussian Approximation for BPSK and QPSK With Asynchronous Cochannel Interference*, IEEE Transactions on Wireless Comm., Vol. 4, No. 2, pp. 384-388, March 2005.

[98] J.G. Proakis, *Digital Communications*, Fourth Ed. New York, McGraw-Hill, 2001.

[99] D.H. Layer, *Digital radio takes to the road*, IEEE Spectrum, Vol. 38, No. 7, pp. 40-46, July 2001.

[100] C.Y. Yeun, *Mobile TV technologies*, in the Proc. of the 5th International Conference on Information and Communications Technology (ICICT), pp. 2-9, 16-18 December 2007, Cairo (Egypt).

[101] 3GPP TR 22.868 v8.0.0, *Study on Facilitating Machine to Machine Communication in 3GPP Systems; Release 8*, March 2007.

[102] European Telecommunication Standardisation Institute (ETSI), Document Draft ETSI TS 102 689 v0.3.1, *Machine-to-Machine communications (M2M); M2M service requirements*, 2009.

[103] C. Pateros, *Novel direct sequence spread spectrum multiple access technique*, MILCOM 2000, 21st Century Military Communications Conference Proceedings, 22-25 October 2000, Los Angeles (USA)

[104] H. Holma, A. Toskala, *WCDMA for UMTS*, John Wiley & Sons, Ltd, 2005.

[105] T. Le-Ngoc, V. Leung, P. Takats and P. Garland, *Interactive Multimedia Satellite Access Communications*, IEEE Communications Magazine, Vol. 41, No. 7, pp. 78-85, July 2003.

[106] C.E. Wheatley III, R. Padovani, E. Zehavi, *Fast forward link power control in a code division multiple access system*, United States Patent No. 5461639, 24 October 1995.

[107] K.S. Gilhousen, R. Padovani, C.E. Wheatley III, *Spread spectrum transmitter power control method and system*, United States Patent No. 5,257,283, 26 October 1993.

[108] A.M. Monk, L.B. Milstein, *Open-loop power control error in a land mobile satellite system*, IEEE Journal on Selected Areas in Communications, Vol. 13, No. 2, pp. 205-212, February 1995.

[109] D. Boudreau, G. Caire, G. E. Corazza, R. De Gaudenzi, G. Gallinaro, M. Luglio, R. Lyons, J. Romero-Garcia, A. Vernucci, H. Widmer, *Wideband CDMA for the Satellite Component ofUMTS/IMT-2000*, IEEE Transactions on Vehicular Technology, Vol. 51, No. 2, pp 306-330, Mar. 2002.

[110] N. Abramson, *Spread aloha CDMA data communications*, United States Patent No. 5537397, 16 July 1996.

[111] Xiang Feng, Yan Li, Guangguo Bi, *A CDMA-slotted ALOHA broadband system for multiservices*, IEEE 1998 International Conference on Universal Personal Communications (ICUPC'98), Vol. 2, pp. 1131-1135, 5-9 October 1998, Florence (Italy).

[112] Y. Tadokoro, H. Okada, T. Yamazato, A. Katayama, A. Ogawa, *A new packet detection scheme in CDMA unslotted ALOHA system with successive interference cancellation*, IEEE Global Telecommunications Conference (Globecom), Vol. 5, pp. 3173-3177, November 2001, San Antonio (USA).

[113] Q. Liu, E.-H. Yang, Z. Zhang, *Throughput analysis of CDMA systems using multiuser receivers*, IEEE Transactions on Communications, Vol. 49 , No. 7, pp. 1192-1202, July 2001.

[114] P. Kota, C. Schlegel, *A wireless packet multiple access method exploiting joint detection*, IEEE International Conference on Communications (ICC), Volume: 4, pp.2985-2989, 11-15 May 2003.

[115] C. Schlegel, R. Kempter, P. Kota, *A novel random wireless packet multiple access method using CDMA*, IEEE Transactions on Wireless Communications, Vol. 5, No. 6, pp. 1362-1370, June 2006.

[116] Karna et al., *"Data transmission method and a radio system*, United States Patent No. 6625138, 23 September 2003.

[117] O. del Río Herrero, R. De Gaudenzi, *A high efficiency scheme for quasi-real-time satellite mobile messaging systems*, Proc. of the 10th International Workshop on Signal Processing for Space Communications, SPSC 2008, pp. 1-9, 6-8 October 2008, Rhodes Island (Greece).

[118] O. del Río Herrero, R. De Gaudenzi, *A High Efficiency Scheme for Large-Scale Satellite Mobile Messaging Systems*, 27th AIAA International Communications Satellite Systems Conference (ICSSC), 1-4 Jun. 2009, Edinburgh (UK).

[119] K. Kim and G. Shevlyakov, *Why Gaussianity?*, IEEE Signal Processing Magazine, March 2008, pp. 102-113.

[120] P. Patel, J. Holtzman, *Analysis of a DS/CDMA successive interference cancellation scheme using correlations,* IEEE Global Telecommunications Conference (Globecom), Vol. 1, pp. 76-80, 29 November - 2 December 1993, Houston (USA).

[121] C. A. Putman, S. S. Rappaport, D. L. Schilling, *A Comparison of Schemes for Coarse Acquisition of Frequency Hopped Spread Spectrum Signals*, IEEE Transactions on Comm., February 1983.

[122] G. E. Corazza, P. Salmi, A. Vanelli-Coralli, M. Villanti, *Differential and non-coherent post detection integration techniques for the return link of satellite W-CDMA systems*, 13th IEEE International Symposium on Personal, Indoor and MobileRadio Communications, Vol. 1, pp. 300- 304, September 2002.

[123] M.K. Sust, R.F. Kaufmann, F. Molitor, G.A. Bjornstrom, *Rapid acquisition concept for voice activated CDMA communication*, Global Telecommunications Conference (Globecom), Vol. 3, pp. 1820-1826, 2-5 December 1990, San Diego (USA).

[124] M.C. Reed, *Acquisition for Satellite UMTS with Large Frequency Offsets*, 5th European Workshop on Mobile/Personal Satcoms (EMPS2002), 25-26 September 2002, Baveno-Stresa, Lake Maggiore (Italy).

[125] 3GPP TS 25.211 v3.12.0, *Physical channels and mapping of transport channels onto physical channels (FDD); Release 1999*, September 2002.

[126] 3GPP TS 25.213 v3.9.0, *Spreading and modulation (FDD); Release 1999*, January 2004.

[127] ETSI TS 101 851-3 V1.1.1, *Satellite Component of the UMTS/IMT2000 A-family; Part 3: Spreading and Modulation* December 2000.

[128] ETSI TS 101 851-4 V1.1.1 Satellite Component of UMTS-IMT 2000;A-family; Part 4: Physical layer procedures, December 2000.

[129] C. E. Gilchriest, *Signal-to-Noise Monitoring*, JPL Space programs Summary, No. 37-27, Vol. IV, pp.169-184, 30 June 1964.

[130] F. Perez-Fontan, M. Vazquez-Castro, C. Enjamio Cabado, J. Pita Garcia, E. Kubista, *Statistical Modelling of the LMS Channel*, IEEE Transactions on Vehicular Technology, Vol. 50, No. 6, November 2001.

[131] F. Perez-Fontan, M. Vazquez-Castro, S. Buonomo, J.P. Poiares-Baptista, B. Arbesser-Rastburg, *S-band LMS channel behaviour for different environments, degrees of shadowing and elevation angles*, IEEE Transactions On Broadcasting, Vol. 44, No. 1, pp. 40-75, March 1998.

[132] ETSI TS 102 584 v1.1.1 *Digital Video Broadcasting (DVB): DVB-SH Implementation Guidelines*, December 2008.

[133] B. Wlodzimierz, *The normal distribution: characterizations with applications*, Springer-Verlag 1995, ISBN 0-387-97990-5.

[134] W. Peter, *An Introduction to Ergodic Theory*, Springer, 1982.

[135] G. Liva, *Graph-Based Analysis and Optimization of Contention Resolution Diversity Slotted ALOHA*, IEEE Transactions on Communications, Vol. 59, Issue 2, pp. 477-487, February 2011.

[136] E. Paolini, G. Liva, M. Chiani, *High Throughput Random Access via Codes on Graphs: Coded Slotted ALOHA*, Proceedings IEEE International Communication Conference (ICC), 5-9 June 2011, Kyoto (Japan).

[137] H.-C. Bui, J. Lacan and M.-L. Boucheret, *An enhanced multiple random access scheme for satellite communications*, In the Proc. of the 2012 Wireless Telecommunications Symposium (WTS), pp. 1-6, 18-20 April 2012, London (United Kingdom).

[138] H.-C. Bui, J. Lacan and M.-L. Boucheret, *Multi-slot coded ALOHA with irregular degree distribution*, In the Proc. of the first International IEEE-AESS Conference in Europe on Space and Satellite Telecommunications (ESTEL), October 2012, Rome (Italy).

[139] F. Ricciato, P. Castiglione, *Pseudo-random Aloha for enhanced collision-recovery in RFID*, IEEE Communications Letters, Vol. 17, No. 3, pp. 608-611, March 2013.

[140] P. Castiglione, F. Ricciato, P. Popovski, Pseudo-Random ALOHA for Inter-frame Soft Combining in RFID Systems, In the Proc. of IEEE 2013 18th International Conference on Digital Signal Processing. 2013.

[141] J. Massey, P. Mathys, *The Collision Channel Without Feedback*, IEEE Transactions on Information Theory, Vol. IT-31, No. 2, pp. 192-204, March 1985.

[142] C. Kissling, *Performance Enhancements for Asynchronous Random Access Protocols over Satellite*, Proceedings IEEE International Communication Conference (ICC), pp. 1-6, 5-9 June 2011, Kyoto (Japan).

[143] F. Clazzer and C. Kissling, *Enhanced Contention Resolution ALOHA - ECRA*, 9th International ITG Conference on Systems, Communications and Coding (SCC), January 2013, Munich (Germany).

[144] O. del Río Herrero, E. Casini, R. De Gaudenzi, *Contention Resolution Diversity Slotted Aloha Plus Demand Assignment (CRDSA-DA): an Enhanced MAC Protocol for Satellite Access Packet Networks*, 23rd AIAA International Communications Satellite Systems Conference, 25-28 Sep. 2005, Rome (Italy).

[145] ETSI TS 102 721-5 v1.1.1, *Satellite Earth Stations and Systems; Air Interface for S-band Mobile Interactive Multimedia (S-MIM); Part 5: Protocol Specifications, Link Layer*, December 2011.

[146] Digital Video Broadcasting (DVB), *Second Generation DVB Interactive Satellite System (DVB-RCS2); Guidelines for Implementation and Use of LLS: EN 301 545-2*, DVB Document A162, February 2013.

[147] J.O. Irwin, *On the Frequency Distribution of the Means of Samples from a Population Having any Law of Frequency with Finite Moments, with Special Reference to Pearson's Type II*, Biometrika, Vol. 19, No. 3/4, pp. 225-239, 1927.

[148] P. Hall, *The Distribution of Means for Samples of Size N Drawn from a Population in which the Variate Takes Values Between 0 and 1, All Such Values Being Equally Probable*, Biometrika, Vol. 19, No. 3/4, pp. 240-245, 1927.

[149] F. Giannetti, M. Luise and R. Reggiannini, *Chip timing recovery in digital modems for continuous-phase CDMA radio communications*, IEEE Transactions on Communications, Vol. 43, Issue 234, pp. 762-766, February/March/April 1995.

[150] Newtec, *Sat3Play IP Broadband System*, http://www.newtec.eu/product/sat3play-ip-broadband-hub.

[151] Viasat, *A Breakthrough in Satellite Communications: The Story of the Technology Behind ArcLight*, Online Journal of Space Communication, Issue 7, VSAT Communication, Fall 2004.

[152] European Space Agency, *Advanced MODEM techniques for future satellite access networks*, ESA Contract Number 4000108548/13/NL/JK, 2013.

[153] F. Collard, R. De Gaudenzi, *On the Optimum Packet Power Distribution for Spread Aloha Packet Detectors with Iterative Successive Interference Cancellation*, IEEE Transactions on Wireless Communications, Vol. 13, No. 12, pp. 6783-6794, October 2014.

[154] G. Gallinaro, N. Alagha, R. De Gaudenzi, K. Kansanen, R. Müller and P. Salvo Rossi, *ME-SSA: an Advanced Random Access for the Satellite Return Channel*, IEEE International Conference on Communications (ICC), 8-12 June 2015, London (UK).

[155] G. Gallinaro, F. Di Cecca, M. Marchitti, R. De Gaudenzi and O. del Río Herrero, *Enhanced spread spectrum ALOHA system level performance assessment*, Wiley International Journal of Satellite Communications and Networking, on-line published November 2013.

[156] C. Kissling, A. Munari *On the integration of random access and DAMA channels for the return link of satellite networks*, IEEE International Conference on Communications (ICC), pp. 4282-4287, 9-13 June 2013, Budapest (Hungary).

[157] C. Stefanovic, K.F. Trilingsgaard, N.K. Pratas, P. Popovski, *Joint estimation and contention-resolution protocol for wireless random access*, IEEE International Conference on Communications (ICC), pp. 3382 - 3387, 9-13 June 2013, Budapest (Hungary).

[158] F. Vazquez-Gallego, M. Rietti, J. Bas, J. Alonso-Zarate, L. Alonso, *Performance Evaluation of Frame Slotted-ALOHA with Succesive Interference Cancellation in Machine-to-Machine Networks*, Proceedings of 20th European Wireless Conference, pp. 1-6, 14-16 May 2014, Barcelona (Spain).

Acronyms

3G	Third Generation
3GPP	Third Generation Partnership Project
ACRDA	Asynchronous Contention Resolution Diversity ALOHA
ARQ	Automatic Repeat request
ATM	Air Traffic Management
ATS	Applications Technology Satellite
AWGN	Additive White Gaussian Noise
BPSK	Binary Phase Shift Keying
BTMA	Busy Tone Multiple Access
CDMA	Code Division Multiple Access
CFDAMA	Combined Free and Demand Assignment Multiple Access
CFDAMA-PB	Combined Free and Demand Assignment Multiple Access - Piggy Backed
CPM	Continuous Phase Modulation
CPODA	Contention Priority Oriented Demand Assignment
CRC	Cyclic Redundancy Check
CRDSA	Contention Resolution Diversity Slotted Aloha
CRDSA-DA	Contention Resolution Diversity Slotted Aloha plus Demand Assignment
CRRMA	Combined Random/Reservation Multiple Access
CSA	Coded Slotted ALOHA
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access / Collision Detection
CTS	Clear To Send
DA	Demand Assignment
DAMA	Demand Assignment Multiple Access
DEA	Diploma Estudis Avançats
DSA	Diversity Slotted ALOHA
DS-CDMA	Direct Sequence - Code Division Multiple Access
DS-SS	Direct Sequence - Spread Spectrum
DTH	Direct To Home
DVB	Digital Video Broadcasting
DVB-RCS	Digital Video Broadcasting - Return Channel Satellite
DVB-RCS2	Digital Video Broadcasting - Return Channel via Satellite second generation
DVB-S2	Digital Video Broadcasting - Satellite
DVB-S2	Digital Video Broadcasting - Satellite - Second Generation
DVB-SH	Digital Video Broadcasting - Satellite services to Handhelds

ECRA	Enhanced Contention Resolution ALOHA
EIRP	Equivalent Isotropically Radiated Power
ESA	European Space Agency
E-SSA	Enhanced Spread-Spectrum ALOHA
ESTEC	European Space Research and Technology Centre
ETSI	European Telecommunications Standards Institute
EUROCAE	European Organisation for Civil Aviation Equipment
FAMA	Floor Acquisition Multiple Access
FCA	Free Capacity Assignment
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FER	Frame Error Rate
FM	Frequency Modulation
GEO	Geostationary Earth Orbit
GMSK	Gaussian Minimum Shift Keying
GPS	Global Positioning System
HD	High Definition
HPA	High Power Amplifier
HTS	High Throughput Satellite
IC	Interference Cancellation
IEEC	Institut Estudis Espacials de Catalunya
IEEE	Institute of Electrical and Electronics Engineers
IFS	Inter Frame Spacing
IP	Internet Protocol
IPoS	IP over Satellite
IRSA	Irregular Repetition Slotted ALOHA
iSIC	iterative Successive Interference Cancellation
ITU	International Telecommunication Union
iTV	interactive TV
LEO	Low Earth Orbit
LMS	Land Mobile Satellite
LNB	Low Noise Block
HEO	Highly Elliptical Orbit
M2M	Machine to Machine
MAC	Medium Access Control
MACA	Multiple Access Collision Avoidance
MACAW	Multiple Access Collision Avoidance for Wireless
MAI	Multiple Access Interference
ME-SSA	MMSE plus Enhanced Spread-Spectrum ALOHA
MF-TDMA	Multi-Frequency - Time Division Multiple Access
MMSE	Minimum Mean Square Error
MMSE-SIC	Minimum Mean Square Error - Successive Interference Cancellation
MUD	Multi User Detection
MuSCA	Multi-Slots Coded ALOHA
NASA	National Aeronautics and Space Administration
NCDP	Network-Coded Diversity Protocol
NTSC	National Television System Committee

PAL	Phase Alternating Line
PCMA	Paired Carrier Multiple Access
PDF	Probability Density Function
PLR	Packet Loss Ratio
PNC	Physical layer Network Coding
PRDAMA	Predictive DAMA
PSK	Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
RA	Random Access
RACH	Random Access Channel
RAN	RA with Notification protocol
RF	Radio-Frequency
RFID	Radio-Frequency Identification
RTN	Return
RTS	Request To Send
S-ALOHA	Slotted Aloha
SCADA	Supervisory control and data acquisition
SD	Standard Definition
SDR	Software Defined Radio
SDUPTC	SNIR Driven Uplink Packet Transmission Control
SECAM	Séquentiel Couleur à Mémoire
SESAR	Single European Sky ATM Research
SF	Spreading Factor
SIC	Successive Interference Cancellation
S-MIM	S-band Mobile Interactive Multimedia
SNIR	Signal to Noise plus Interference Ratio
SNR	Signal to Noise Ratio
SSA	Spread Spectrum ALOHA
SSMA	Spread Spectrum Multiple Access
SUMF	Single User Matched Filter
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TIA	Telecommunication Industry Association
TT&C	Telemetry, Tracking and Command
TV	Television
UHF	Ultra-High Frequency
UMTS	Universal Mobile Telecommunications System
UW	Unique Word
VF	Virtual Frame
VSAT	Very Small Aperture Terminal