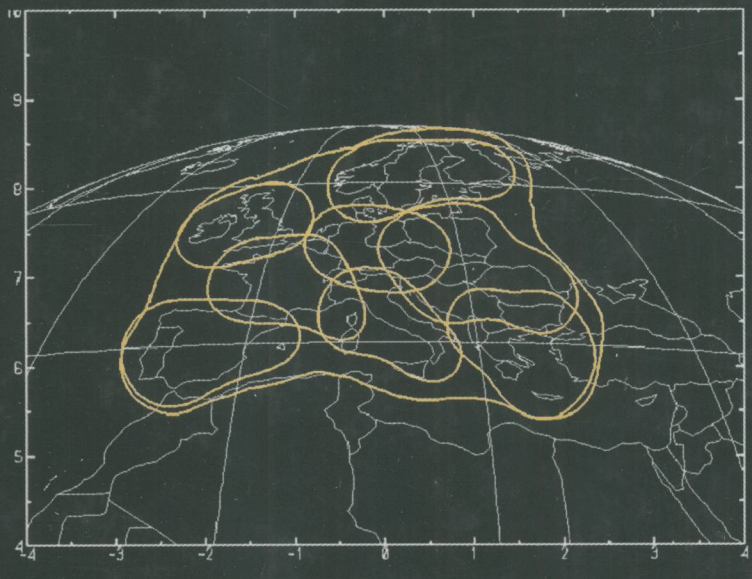
An Experimental Approach to CDMA and Interference Mitigation

From System Architecture to Hardware Testing through VLSI Design

by
Luca Fanucci,
Filippo Giannetti,
Marco Luise and
Massimo Rovini



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AN EXPERIMENTAL APPROACH TO CDMA AND INTERFERENCE MITIGATION

Authors

Luca Fanucci was born in Montecatini Terme, Italy, in 1965. He received the Doctor Engineer (summa cum laude) and the Research Doctor degrees, both in electronic engineering, from the University of Pisa, Pisa, Italy, in 1992 and 1996, respectively. From 1992 to 1996, he was with the European Space Agency's Research and Technology Center, Noordwijk, The Netherlands, where he was involved in several activities in the field of VLSI for digital communications. He is currently a Research Scientist of the Italian National Research Council in Pisa. Since 2000, he has been an Assistant Professor of Microelectronics at the University of Pisa, Italy. His main interests are in the areas of System-on-Chip design, low power systems, VLSI architectures for real-time image and signal processing, and applications of VLSI technology to digital and RF communication systems.

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in mobile and satellite communications, synchronization and spread-spectrum systems.

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Foreword

My first touch with Code Division Multiple Access (CDMA) was during my early days at the European Space Agency (ESA) when I was involved with the development of an accurate geostationary satellite tracking system exploiting Direct Sequence CDMA. I distinctly recall the surprise to hear from my supervisor that *"the spread spectrum technique allows transmitting signals below the thermal noise floor"*. The statement was intriguing enough for me to enthusiastically accept working on the subject. I immediately fell in love with CDMA systems, as they soon revealed (both to my dismal and to my pleasure) being complex enough to keep me busy for more than a decade.

Shortly after moving to the ESA's main R&D establishment in the Netherlands, I started to regard CDMA as a potential candidate for satellite fixed and mobile communication networks. It was a pioneering and exciting time, when CDMA was still confined to military, professional and navigation applications. At ESA we developed preliminary architectures of CDMA systems featuring band limited signals, and free of self noise interference trough a simple yet efficient approach based on tight code epoch synchronization. Concurrently, we also started the earliest CDMA digital satellite modems development. The laboratory experiments unveiling the ups and downs of (quasi-)orthogonal CDMA interference where shortly after followed by the first satellite tests.

At that time a small US-based company named *Qualcomm* was moving the first steps in making CDMA technology for terrestrial cellular telephony truly commercial. And the fact that the co-founders of this small company were Dr. A.J. Viterbi and Dr. I.J. Jacobs convinced the management of ESA to financially support our modest R&D effort. While the 'religious' battle

between the TDMA and CDMA terrestrial armies was taking momentum, in our little corner we went on studying, understanding, experimenting, and improving on CDMA technologies.

I had then the pleasure to closely follow the development of ESA's first mobile and fixed CDMA satellite networks while witnessing the commercial deployment of the first terrestrial CDMA networks (IS-95), and directly participating to the early tests with the Globalstar satellite mobile telephony system during my stay at Qualcomm in '96–'97. Since then CDMA technology started becoming the subject of industry courses, University lectures, and was often appearing on the front page of non-technical newspapers and magazines.

The final battle corresponded to the selection of CDMA in several flavors as the air interface for the 3rd Generation (3G) of personal communication systems: Universal Mobile Telecommunication Systems (UMTS) in Europe and Japan, and cdma2000 in the Americas. During the early days I also convinced my friend and former ESA colleagues Marco Luise and Filippo Giannetti, shortly followed by Luca Fanucci, to join the excitement and the frustrations of the satellite CDMA camp, and this was maybe the initial seed that later bloomed into this book.

While 'classical' CDMA technologies where getting commercially deployed, a truly remarkable investigation effort was taking place in the academic world about the issue of Multi User Detection (MUD) and Interference Mitigation (IM). MUD issues attracted the interest of hundreds of researchers around the world despite an initial skepticism about its effectiveness. With the authors of the book I was also 'contaminated' by the idea to develop more advanced CDMA detectors which can autonomously remove the CDMA self noise. But browsing hundreds of papers on the subject, we were still missing inspiration for some technique which can be readily implemented in the user terminal of a satellite network.

Finally, in the mid nineties we get acquainted with the work by Honig, Madhow and Verdù, and so we get convinced that interference mitigation could be really done and could work fine in a wireless satellite network. This was the beginning of the endeavor described in this book, where a small group of people from Academia, with the due technical support from a big semiconductor firm, where able to put together possibly the first ASIC-based CDMA interference mitigating detector ever. But this is just the beginning of a new era which I am sure will be as exciting as the previous decade.

Probably the most prominent Italian novelist, Alessandro Manzoni (1785–1873) used to modestly address his largely vast readership as *"my twenty-five readers"*. I am convinced that this book, too, will find (not the same!) twenty-five people that will enjoy and appreciate the spirit and lessons learnt during this remarkable adventure, as if they were themselves part

of the team which carried out this exciting project financed by the ESA Technology Research Plan.

Riccardo De Gaudenzi

Head of the Communication Systems Section
European Space Research and Technology Centre
European Space Agency

Noordwijk (The Netherlands), July 2003

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Chapter 1

INTRODUCING WIRELESS COMMUNICATIONS

"Life will not be the same after the wireless revolution". This is certainly true at the moment for countries in the Western world, and is going to be true in a few years for developing countries as well. So the aim of this Chapter is first to address the main terms of this revolution from the technical standpoint and to review the main second- and third-generation worldwide standards for wireless cellular communication, then to discuss how satellites can play a role in this scenario, and finally to show how this 'revolution' could have taken place through the tremendous technological progress of (micro-)electronics.

1. THE WIRELESS REVOLUTION

In many European countries the number of *wireless* access connections between the user terminals (cellular phones, laptops, palmtops, etc.) and the fixed, high capacity transport network has already exceeded the number of *wired* connections. Untethered communications and computing has ultimately become part of a lifestyle, and the trend will undoubtedly go further in the near future, with the commercialization of low cost *Wireless Local Area Networks* (WLANs) for the home. Round the corner we may also envisage pervasive, *ad hoc* wireless networks of sensors and user terminals communicating directly with each other via multiple hops, and without any need of support from the transport network.

The picture we have just depicted is what we may call the *wireless revolution* [Rap91]. Started in Europe in the early 90s, with the American countries lagging by a few years, it will probably come to its full evolution within the end of the first decade of the third century, to rise again in a second great tidal wave when the Asian developing countries will catch up [Sas98]. The real start of the revolution was the advent in Europe of the so called 2^{nd} *Gen-*

eration (2G), digital, pan-European cellular communication systems, the well known GSM (Global System for Mobile communications) [Pad95]. The explosive growth of cellular communications had already started with earlier analog systems, the so called *1st Generation* (1G), but the real breakthrough was marked by the initially slow, then exponential, diffusion of GSM terminals, fostered by continent wide compatibility through international roaming. In the United States the advent of 2G digital systems was somewhat slowed down by the co-existence of incompatible systems and by the consequent lack of a nation wide accepted unique standard. The two competing 2G American standards are the so called 'digital' AMPS (Advanced Mobile Phone System) IS-154 whose technology was developed with the specific aim of being compatible (as far as the assigned RF channels are concerned) with the pre-existing 1G analog AMPS system, and the highly innovative *Code Division Multiple Access* (CDMA) system IS-95.

In the second half of the 90s the GSM proved highly effective, boomed in Europe, and was adopted in many other countries across the whole world, including Australia, India, and most Asian countries. The initial European allocation of radio channels close to 900 MHz was paired by an additional allocation close to 1800 MHz (DCS-1800 system) that led to the tripling of system capacity. GSM techniques were also 'exported' to the United States under the label of PCS (Personal Communication Systems) with an allocation of channels close to 1900 MHz. At the turn of the century GSM, through its mature technology, started to be exploited as a true born digital system, delivering multimedia contents (paging, messaging, still images, and short videoclips). It is also being extended and augmented into a packet access radio network through the GPRS (Generalized Packet Radio Service) access mode (Figure 1-1), and will also be augmented to higher capacity through the EDGE (Enhanced Data rate for Global Evolution) technology. Both GPRS and EDGE are labeled '2.5G technologies', since they represent the bridge towards *3rd Generation* (3G) systems which will be discussed later.

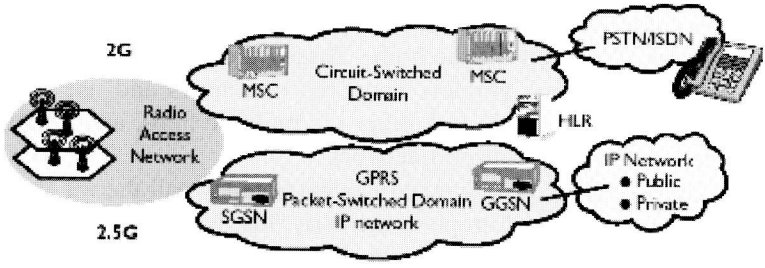

Figure 1-1. GSM/GPRS Network Architecture (http://www.gsm.org).

A similar evolution has taken place in the United States with CDMA IS-95 2G systems (Figure 1-2) [Koh95], [Gil91]. After a controversial start in the area of California, CDMA systems were early adopted in Brazil, Russia, and Korea. They soon evolved into an articulated family of different systems and technologies called cdmaOne, all based on the original standard IS-95 and its evolutions. After 'cellular CDMA' at 800 MHz was launched its PCS version at 1900 MHz was soon made available. Packet access was embedded into the system, and a standard for *fixed* radio terminals to provide fixed wireless access to the transport network was also added. We shall not insist further on the evolution of 1G and 2-2.5G systems in Japan, not to play again a well known song.

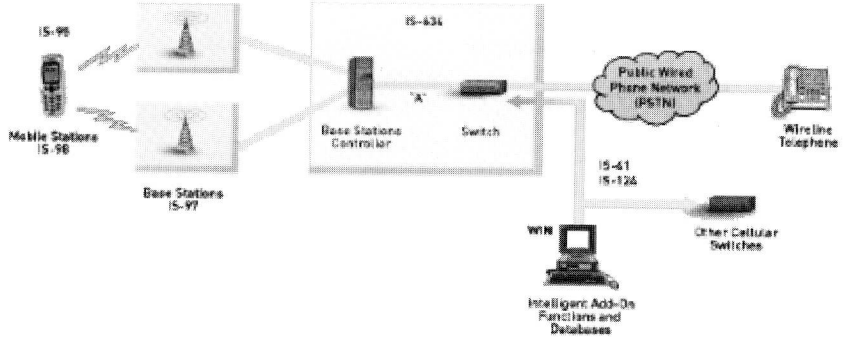

Figure 1-2. Network architecture of an IS-95 CDMA system (http://www.cdg.org).

At the dawn of the third millennium the ITU (International Telecommunications Union), based in Geneva, took the initiative of promoting the development of a universal 3G mobile/personal wireless communication system with high capacity and a high degree of inter-operability among the different network components, as depicted in Figure 1-3. Under the initiative IMT-2000 (International Mobile Telecommunications for the year 2000) [Chi92] a call for proposals was issued in 1997 to eventually set up the specifications and the technical recommendations for a universal system. At the end of the selection procedure, and in response to the different needs of the national industries, operators, and PTTs, two different non-compatible standards survived: UMTS (Universal Mobile Telecommunication System) for Europe and Japan, and cdma2000 for the USA. Both are based on a mixture of time and code division multiple access technologies. UMTS stems from a number of research projects carried out in the past by Europe and Ja-

pan (mainly FRAMES in Europe [Dah98] and CORE-A in Japan [Ada98]), whilst cdma2000, following a consolidated tradition in the standardization procedures in the United States, is a backwards compatible evolution of 2G CDMA [Kni98]. 3G systems are being developed at the time of the writing of this Chapter (early 2003), with Japan leading the group. Some are questioning the commercial validity of 3G systems (but this is something completely outside the scope of this book), other say that 3G will not reveal such a breakthrough as 2G systems have admittedly been. We will say more on 2G/3G systems in Section 1.2.

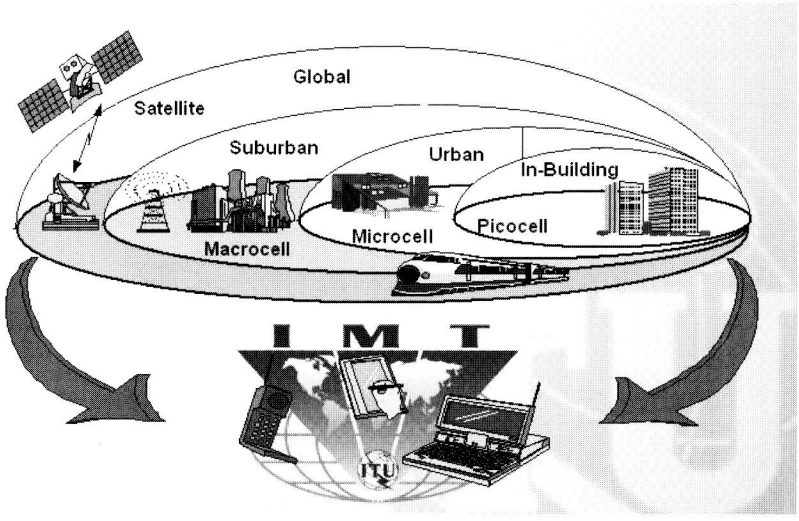

Figure 1-3. IMT-2000 system concept (http://www.itu.org).

The next wave of the wireless revolution may possibly come from WLANs [Nee99]. A WLAN is not just a replacement of a traditional wired LAN (such as the ubiquitous Ethernet in one of its 10/100/1000 Mbit/s versions). Many forecasts envisage, in fact, a co-existence between wired copper LANs to link fixed PCs within an office (or a building) and wireless networks (the WLANs) yielding high bit rate together with a certain support of mobility and handovers. With WLANs laptops, palmtops, possibly portable mp3 players and/or videoterminals, are all linked together, either via a central access point in a star topology (with immediate provision of connectivity with the fixed network), or directly with each other in an 'ad hoc', decentralized architecture. The former architecture is typical of IEEE 802.11a–b networks that are at the moment gaining more and more popularity; the latter is the paradigm of Bluetooth pico-nets/scatter-nets and of IEEE 802.15

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