CONCEPTION AND PERFORMANCE OF THE CELLULAR DIGITAL MOBILE RADIO COMMUNICATION SYSTEM CD 900

K.D. Eckert

Standard Elektrik Lorenz AG
RDE Radio and Navigation
Stuttgart, FRG

ABSTRACT

The cellular digital radio communication system CD 900 supplies millions of mobile subscribers per network with voice and data service. It applies a digital wideband TDMA-process allowing up to 330 traffic channels within 24 MHz to be allocated to one base station. A cluster of three becomes possible by its excellent interference suppression features resulting from the utilization of multipath signals by an adaptive matched filtering process realized with a digital signal processor. CD 900 is designed as to satisfy the demand for a mobile communication mass market as well as for its adaption to modern digital transmission networks including ISDN.

INTRODUCTION

The performances of communication and traffic networks are important prerequisites for the power and efficiency of any national economy. In consequence big efforts were made in the highly industrialized countries in both areas, the communication networks and the traffic infrastructure, being illustrated by the growth of the number of cars and fixed telephone subscribers in the FRG for instance (see Fig. 1).

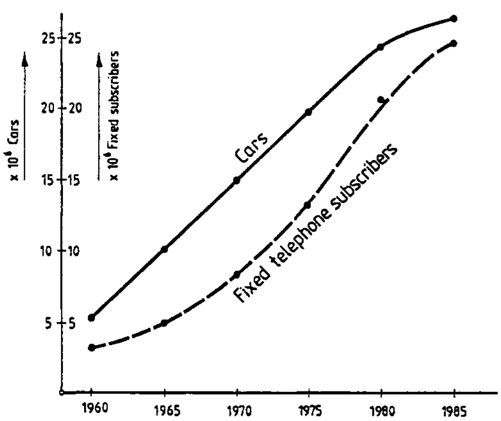

Fig. 1 Development of Car and Fixed Telephone Subscriber Density in the FRG

In most of the European countries however only a small fraction of the big number of operating cars are equipped with radio telephone sets, in contrast to the high density of fixed telephones connected to the public switching telephone networks. This unbalance results from the following:

- Purchase and installation of mobile subscriber equipment is very expensive. This is caused by the relatively small number of manufactured devices which does not permit strong cost reduction effort.

- Operation of mobile radio telephone is a costly service. The lag of radio channels available caused the operating administrations to request prohibitively high call-charges in order to limit conversation time and to organize simultaneous system access for as many subscribers as possible.

- Quality and manifold of the services of the existing mobile radio telephone networks are not sufficiently comfortable as to attract as large a number of subscribers as needed to initiate a real mass market.

Moreover the actual communication networks are subjected now and in the early nineties to some far reaching changes for improvement of their performances and efficiency. Two of the most important steps of this process are:

- The move from analog communication networks towards fully digital networks resulting in the worldwide introduction of the integrated services digital network ISDN.

- The extension of the existing fixed communication networks to mobile users on the ground and on water.

While the digitalization of the fixed networks is making good progress already, the establishment of sophisticated mobile communication systems is still at its initial stage regarding its introduction as a high performance service for the general public.

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SERVICES AND PERFORMANCES REQUIRED

Modern mobile radio communication systems must satisfy some basic operational and technical requirements to get that broad acceptance our fixed telephone networks already have:

- High traffic capacity in order to serve several millions of subscribers per network.
- Because of the physically finite number of radio frequencies modern mobile radio telephone systems must take care to practice sophisticated frequency economy.
- Good quality of transmission with high interference immunity is mandatory for any new mobile radio communication system.
- System flexibility offering fully automatic duplex service, automatic handover and roaming over the full network area are absolute musts. In addition, any care has to be taken to protect transmitted information from being misused, thus keeping full transmission privacy.
- Services offered must not be limited to pure voice communication but moreover have to comprise various types of data transmission as well as other additional services like emergency calls, paging services etc. in order to become sufficiently attractive for the potential subscribers.
- Subscriber equipment as well as network infrastructure must be inexpensive though efficient and future oriented enough as to attract potential subscribers in numbers of millions per network.

It is obvious, that the traditional mobile radio communication systems in service today at the 150 MHz and the 450 MHz band can not cope with these requirements particularly regarding the expected high number of subscribers. From this two consequences resulted in Europe:

* In 1979 the World Administrative Radio Conference WARC allocated the 860 to 960 MHz radio frequency band to future mobile services. Out of this band 2 x 25 MHz for duplex service have been devoted for mobile radio communication services.
* In 1983 the "Groupe Spéciale Service Mobile" (GSM) of the CEPT (Conférence Européenne des Administrations des Postes et des Télécommunications) started work aiming at a paneuropean standard of a future mobile radio communication system at 900 MHz. Having started this work with a broad analysis, GSM decided in early 1985 to fully concentrate on systems using digital transmission.

In support of the GSM activities some european PTTs started to investigate various digital radio transmission concepts by ordering and testing corresponding validation systems at the industry, one of them having been CD 900.

A decision on the paneuropean digital radio communication system at 900 MHz is expected to be taken by GSM and CEPT in the course of 1987, permitting industry to start system development in 1988. The start of service of the paneuropean digital mobile communication system is envisaged for the early nineties [1].

DIGITAL TRANSMISSION, THE FAVOURED SOLUTION

Traditional mobile radio telephone systems apply analog transmission of voice signals for instance by frequency-modulating the analog voice signal on a RF-carrier. This signal is then transmitted in a FDM access mode as a "single channel per carrier" (SCPC)-transmission.

Today, however, the whole fixed transmission network is getting digitized more and more aiming at the realization of an overall ISDN-network, the voice-transmission being only one element of the ISDN performance spectrum.

Consequently operators and administrations as well as industry drew their attention more and more towards the extension of digital transmission also into the field of radio transmission for mobile services. The introduction of digital radio transmission into the mobile communication services closes the gap until now preventing a full end to end digital service between a fixed and a mobile subscriber. The introduction of digital switching systems and digital transmission systems, finally resulting in the Integrated Services Digital Network (ISDN), forms the environment of modern mobile radio telephone networks. Services such as telephone, telex, telefax or various types of data services will be integrated into one network leading to a "64 kbit/s environment" for handling most of the telecom services.

This resulted in the following features for the radio channel:

* The introduction of digital radio transmission allows the application of a time division multiple access (TDMA) architecture. Special selection of the signal format combined with moderate spectrum spreading and appropriate digital signal processing techniques not only allow to cope with but also to make use of multipath propagation resulting in high levels of reception performance and immunity against co-channel interferences.
* This digital wideband transmission can be realized by applying not only a TDMA-process but in addition by the use of code division multiple access (CDMA) and frequency division multiple access (FDMA). By this the system performances with respect to the number of subscribers and to the frequency economy become superior to the traditional conceptions. Moreover, a wideband system requires only one transmitter and one receiver at each base station handling all traffic channels in sequence (TDMA), thus offering significant cost advantages compared to SCPC-conceptions.

* In order to establish a mobile radio communication system serving really big numbers of subscribers per network the cost of the mobile equipment and the operating cost have to be kept sufficiently low as to be affordable by an average subscriber. The digital transmission permits the broad introduction of digital signal processing executed by only some VLSJ-circuits resulting in a significant cut of production cost especially for the mobile devices. Thus, digital wideband transmission is a mandatory prequisite for a future mobile communication system designed to attract several millions of subscribers per network.

STRUCTURE OF CELLULAR MOBILE COMMUNICATION SYSTEMS

Mobile communication networks apply cellular structures to provide the required high number of traffic channels (TCH) by repeating the same channel-determining parameters at cells sufficiently apart to limit mutual interferences.

Optimum cell size is influenced by two contradictory sets of parameters. Parameters calling for large cells are cost of infrastructure, frequency of hand-over and roaming procedures, while parameters calling for small cells are frequency economy and propagation at 900 MHz (topography). As a compromise, a cell radius of about 10 km has emerged, although it may vary depending on the traffic situation and other parameters.

In this context, two possible network structures can be envisioned:

- The overlay-type network (Fig. 2a), where all base stations are connected to mobile switching centers (MSC). Thus they form a separate "overlay" network linked to the public switched telephone network (PSTN) at discrete nodes, the gateways.

- The integrated network (Fig. 2b), where each BS is directly linked to an ISDN exchange, thus integrating the mobile communication system into the ISDN.

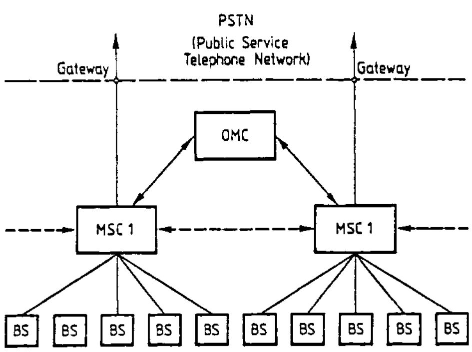

Fig. 2a Overlay Network for DMRS

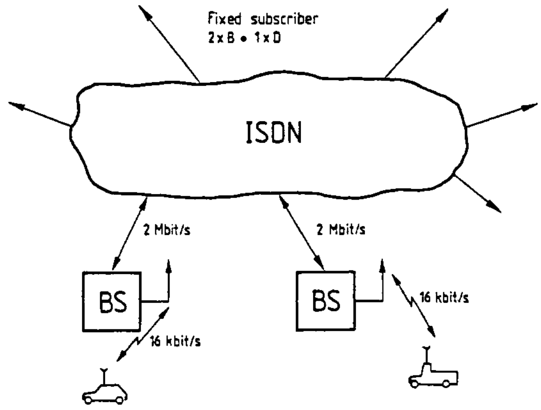

Fig. 2b DMRS ISDN Network Structure

While the overlay solution conforms to traditional telephone networks' design, the integrated concept will be the solution of the future.

THE CD 900 CONCEPTION

The cellular digital mobile radio communication system CD 900 is designed as to satisfy the mentioned basic requirements

- high system capacity
- good frequency economy
- good quality of transmission
- wide choice of services
- low cost.

CD 900 will achieve this by using a wideband digital radio transmission, an efficient and flexible design of the mobile station (MS) and the corresponding hand-held telephone (HT) and the base station (BS), by advanced digital switching systems and ISDN capable digital interfaces [2].

When planning the CD 900 cellular digital radio telephone system a figure of more than a million mobile subscribers distributed over the coverage of the FRG of about 250 000 km² was taken as a basis. Each subscriber generates a traffic intensity of 0.015 Erlang during peak traffic period, which means that 15 000 calls can take place simultaneously.

This high volume of voice channels is normally provided in a cellular system structure by repeating the same voice channels in a number of cells whilst preserving a reasonable interference margin. Different voice channels must only be used in directly adjacent cells in order to avoid mutual interference. Whereas in narrow-band systems this type of group (cluster) is formed by seven or more cells, the CD 900 manages with only three cells per group on account of the low signal-to-noise ratio necessary with digital transmission.

An important parameter of the CD 900 system structure is the size of the cell. Considerations regarding frequency economy, interference conditions, radio propagation at 900 MHz and cost of infrastructure resulted in a "mean" cell radius of 10 km (= surface area approx. 315 km²) which was taken as guideline for CD 900. With respect to the above mentioned amount of traffic (15 mE/SC + 100 % reserve) the normalized capacity requirement is about 38 voice channels per BS.

The centre of each cell is a base station (BS) which establishes the radio transmission to the mobile subscriber station (MS) in the coverage area of the cell. Each cell in the CD 900 system comprises 3 sectors, each illuminated by an antenna. As shown in Fig. 3, the sector does not remain constant but rather is matched to a suitable radiation pattern required by the topography. Idealized the sector can be taken as being hexagonal and by combining several cells a fully area covering network obviously can be formed (Fig. 4).

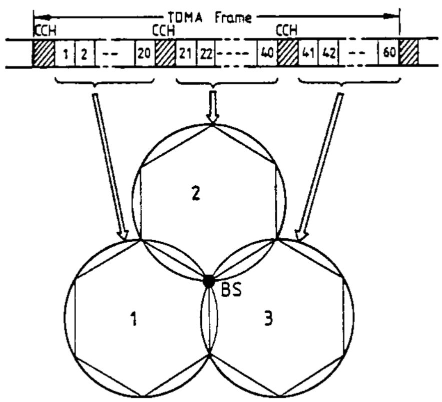

Fig. 3a CD 900 Cell with 3 Sectors

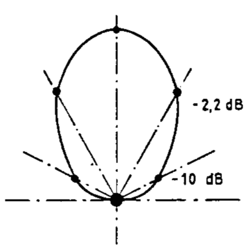

Fig. 3b Pattern of Sector Antenna

Each base station operates as a radio concentrator permitting access to the system for several mobile users. The access process applied in the CD 900 system is a time division multiple access TDMA. This means that a CD 900 channel is a periodically recurring time slot in which an information transfer takes place between the mobile subscriber and a base station.

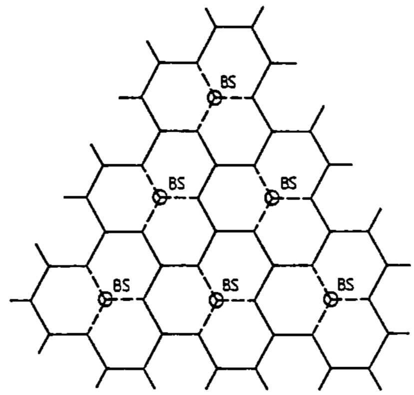

Fig. 4 CD 900 Cell Network

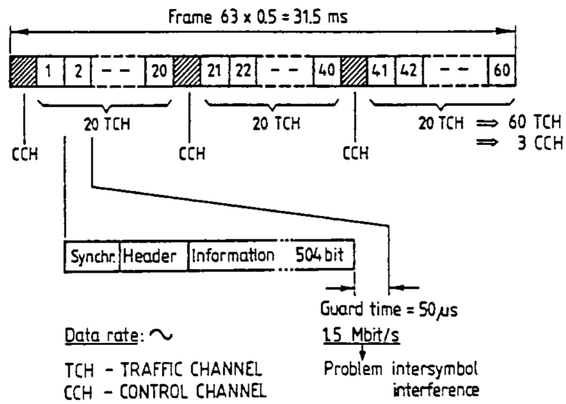

Fig. 5 CD 900 TDMA Structure

The resulting TDMA-structure is shown in Fig. 5. The time frame of 31.5 ms which comprises all channels (= timeslot) allocated to a base station is composed of 63 timeslots subdivided into three sections each of which belongs to one of the three sectors of a BS. In the case of equally distributed traffic each sector offers 20 traffic channels plus one organization channel being operated in sequence by connecting the transmit/receive unit of the BS to sector antenna 1, 2 or 3.

The timeslot itself, having a width of 0.5 ms, again is subdivided into 4 sections. Starting with a synchronization preamble required to detect the start of a timeslot in the receiver then followed by the so-called header section which carries in-channel organizational data, the main section contains the speech or data information to be transmitted. At the end of a timeslot a guard time is foreseen to cope with varying propagation times between MS and BS. According to the transmission of digitized speech in a comparably small timeslot, the radio transmission operates in a wideband mode resulting in only one broadband radio frequency channel for all base stations and another one for all mobile units.

On the side of the fixed net of the CD 900 system, mobile services switching centres - MSC - are connected to several base stations (Fig. 2a). The MSCs are responsible for all call-processing tasks related to set-up and cleardown of calls as well as for numerous organizational functions related to the administration of the network and for interfacing the CD 900 network to the PSTN.

THE CD 900 DIGITAL WIDEBAND RADIO TRANSMISSION

The radio transmission process is one of the key elements of a mobile radio communication system. Its characteristics not only determine the quality of voice or data transmission between base station and mobile station but in addition do have a significant impact on the organizational conception of the system [3].

Propagation under adverse conditions as multipath, shadowing, adjacent cell interferences, man-made and natural noise impact on the quality of the transmitted information. The high data rate of about 1.5 Mbit/s resulting from the CD 900 TDMA-process is adding intersymbol interferences to this transmission deficiencies. To cope with that difficulties the CD 900 radio transmission is based on the idea to utilize multipath propagation and to suppress intersymbol interferences by the application of moderate spectrum spreading and sophisticated digital signal processing.

Due to the fact, that every transmission path conveys signal energy carrying the full information, it is advisible to make use of this signal energy elements by an appropriate signal detection and integration process (Fig. 6). The resolution of transmission paths running detour from the direct MS-BS antenna connection via according reflectors needs a fine resolution of the received signal in the time domain. This process requires bandwidth which in CD 900 stems from a moderate spectrum spreading process applied.

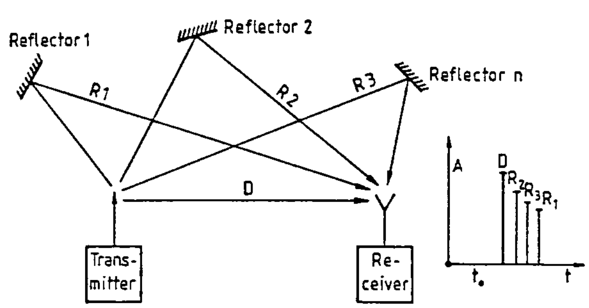

Fig. 6 Radio Signal Propagation

This spectrum spreading process is achieved in transmitting the message by the aid of codewords having a length of 32 code bits, also known as chips (Fig. 7). The character alphabet selected has

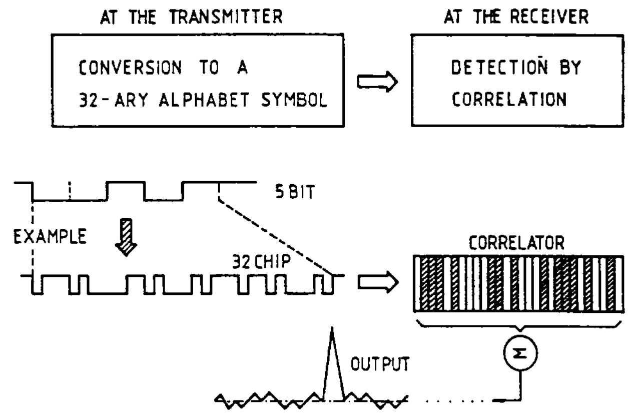

Fig. 7 Spread Spectrum Coding

32 different basic symbols clearly identifyable by their chip sequence. This 32 basic characters form a orthogonal alphabet. Each of the 32 codewords in the transmitter has the information content of 5 bit. The zero phase angle of the received signal is determined in the receiver. Thus for each of the 32 basic symbols it is also possible to use the inverted signal, whereby the information content is increased from 5 bits to 6 bits for each transmitted signal. Moreover, the reconstructability of the zero phase angle permits two independent chip sequences in phase quadrature to be transmitted and detected in the receiver simultaneously. This method of transmission in quadrature components, known as quadrature phase shift keying (QPSK), enables 12 bits to be transmitted during a time interval corresponding to 32 chips. This results in a spreading factor of 2.67. The technical realization of an according transmitter section is shown in Fig. 8.

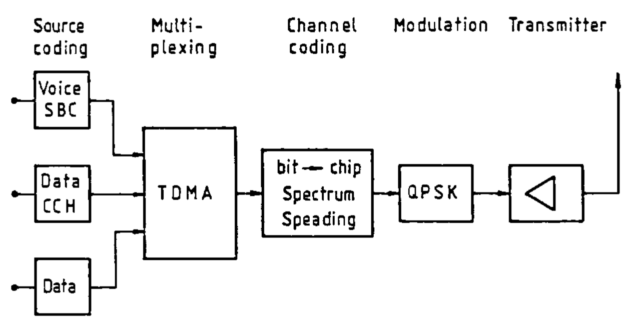

Fig. 8 CD 900 Transmitter Principle

The conception of the CD 900 receiver was guided by two important topics:

* To do a design which is capable of coping with various types of interfering effects in particular by utilizing multipath signals.

* To do a fully digital design which allows even complex signal processing to be packaged into inexpensive LSI-type signal processors supported by powerful software.

The solution which was found satisfies these requirements by executing the process of evaluation of received CD 900 signals in a 3-step procedure according to the simplified block diagram of receiver operation as given in Fig. 9.

The three most important steps in CD 900 receiver signal processing are:

- to perform matched filtering
- to correlate with replicas of the 32-ary alphabet
- to decide which word may have been transmitted.

For matched filtering the CD 900 signal format has been designed enabling the receiver to measure the actual channel impulse response which, after time inversion, represents the impulse response of the matched filter.

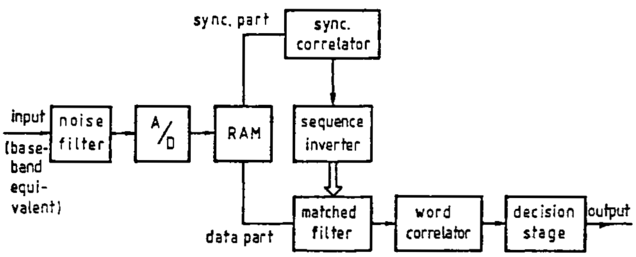

Fig. 9 CD 900 Receiver Operation

The baseband equivalent of the input signal, comprising the wanted signal, white gaussian noise and co-channel interference, is bandlimited in a prefilter. After A/D-conversion samples are stored in a random access memory and are available for further processing during the time until the next receive timeslot occurs. The channel impulse response is revealed by feeding the synchronization part of the received waveform to the sync correlator. The correlation not only displays the dispersion introduced by the present multipath profile but also all filtering effects on the transmitter and receiver side. The sync preamble is a pseudorandom sequence of 127 chips, giving a processing gain of more than 20 dB, so the measurement is very accurate.

The problems of chip synchronization and carrier phase detection are likewise automatically solved, the first by the fact that the channel impulse response is derived from samples having been taken in the same sampling pattern as those in the message part. The carrier phase directly reflects itself in the complex-valued channel impulse response. Tasks left are to correct for the rotation introduced by oscillator frequency offsets between transmitter and receiver and to adapt to the Doppler effect due to vehicle movements. So the matched filtering process is automatically chip synchronized and, as is well known from theory, yields an output proportional to the totally available energy per chip. Since all resolved paths of the propagation medium are included, multipath propagation contributes to improve the transmission reliability.

Word correlation as the next step of signal processing means that all contiguous 32-chip strings of the data part coming out of the matched filter are tested against each of the words of the alphabet. In the decision stage the decision is made in favour of the word yielding the largest correlation result. Although the transmission in phase quadrature results in a 3 dB loss the time bandwidth product of 32, equivalent to 15 dB, assures high immunity against noise and forms a good basis to widely suppress intersymbol as well as co-channel interference [4].

ACCESS PROCEDURES APPLIED AT CD 900

Some aspects regarding utilization of several access procedures by CD 900 shall now be discussed, completing the considerations of CD 900 radio transmission. In addition to the fundamental TDMA-procedure, CD 900 also makes use of a certain code division procedure (Fig. 10). By overlaying the transmitted signals of adjacent cells with different PN-codes of excellent correlation properties (M-sequences) the adjacent cell interference immunity gets increased significantly by forming "code-clusters" of three. Moreover, CD 900 does apply FDMA-features too. Allocating 6 MHz bandwidth to a base station allows for the installation of 60 traffic channels. The full frequency band available for public mobile services according to WARC 79, however, comprises 25 MHz. Thus 4 different 6 MHz bands can be operated simultaneously per BS, resulting in a total of 240 traffic channels per BS. This figure illustrates the good frequency economy of CD 900, because it is about 1.7 ... 2.4 times (depending on cluster factor) the number of traffic channels available in a conventional FDMA 25 kHz mobile radio system of same spectrum occupancy (Fig. 11).

The choice of subdividing the 25-MHz band available per direction into 4 x 6 MHz subbands however is not mandatory and not the only one possible. Other choices between 2 MHz and 6 MHz are possible thus coping with varying requirements.

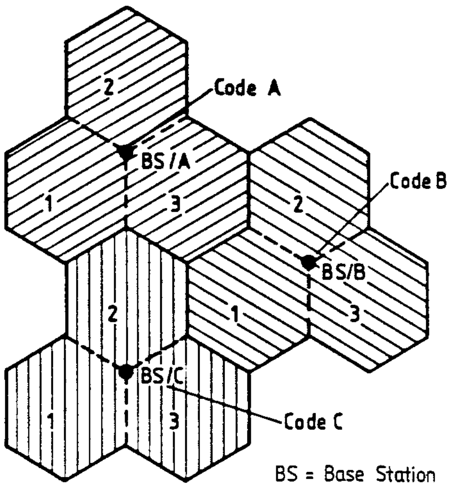

Fig. 10 CD 900 3 Cell Cluster

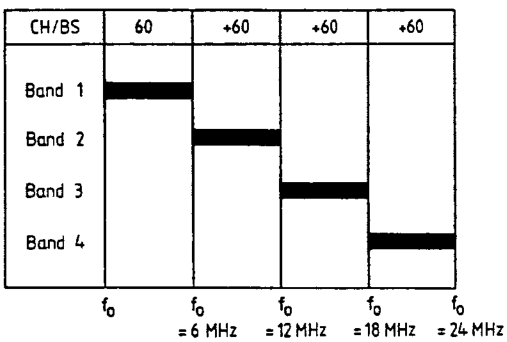

Fig. 11 CD 900 Frequency Band Overlay

PERFORMANCE OF CD 900 RADIO TRANSMISSION

For assessment of the transmission performance of CD 900 a set of radio transmission validation systems CD 900 VS have been designed, built and tested. Each validation system comprised 1 base station and 1 mobile station being equipped with 3 traffic channels (TCH) per base station and 3 associated control channels (ACCH) accordingly, the mobile station operating with one TCH. The services offered by the CD 900 VS are

- Transmission of digitized voice with 16 kbit/s via TCH
- Digital data transmission via TCH gross rate 16 kbit/s
- Protected data transmission via ACCH net rate 800 bit/s
- Transparent data transmission via vocoder + TCH with rates up to 2400 Baud.

In addition to this transmission channel simulators have been designed and built allowing for the simulation of various transmission anomalies like fading, multipath propagation, doppler effect, noise etc.

Test, which have been performed with this configuration comprised

- Lab tests: RF-testing, stationary and dynamic testing of transmission performance by BER-measurements at different transmission scenarios
- Field tests: Propagation investigations, assessment of multipath profiles, dynamic field tests in rural and urban environment (i.e. cities of Stuttgart/FRG and Paris/France) by continuous BER-measurement and subjective assessment of received voice at the mobile equipment and the base station as well.

Executing these tests, the following results have been achieved normally being measured against a bit error rate (BER) of 1 % being found to be fully satisfactory for proper vocoder operation.

- Stationary tests:
  - Resistance against noise:
    $E_b/N_0 \approx 3.2$ dB (Theory: 2.5 dB)
  - Resistance against interference:
    C/I = -1 dB (Theory: -2 dB)
- Dynamic tests:
  - Rayleigh fading: 2 path model; C/N ≈ 20 dB
    MP-spread: 0.3 ... 8 μs ⟶ BER: $1.5 \cdot 10^{-3}$ ... $2.7 \cdot 10^{-3}$
  - Rural multipath profile:
    100 km/h: C/N = 7.2 dB for 1 % BER
    200 km/h: C/N ≈ 8.3 dB for 1 % BER
  - Co-channel interference in a bad urban multipath environment:
    For 1 % BER required C/I = 3.4 dB (Theory: 2.6 dB)
    For 2 % BER required C/I ≈ 1.6 dB

In addition to these lab test results Fig. 12 shows BER-values as a function of received signal strength measured during 6 testruns at different places at the city of Paris in France. It clearly indicates, that down to -100 dBm the required BER of <1 % can be guaranteed.

All BER measurement taken over 6 measurement parcours.
Transmitted power at antenna feed:
16 W burst peak.

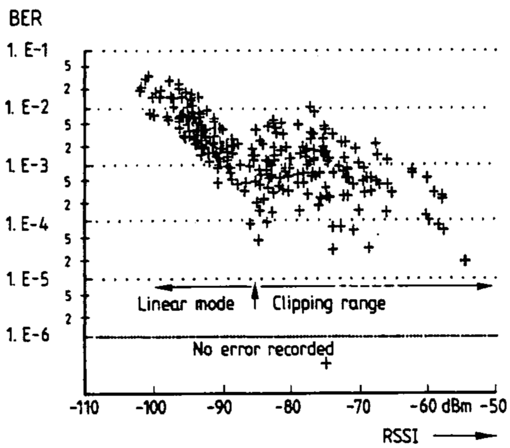

Fig. 12 CD 900 VS Field Test Results

CONSIDERATION ON CD 900 NETWORK STRUCTURE

The CD 900 network will be part of a network design presenting 4 different levels of hierarchy:

* The level of the public switched telephone network (PSTN)
* The level of mobile services switching centers (MSC)
* The level of base stations (BS)
* The level of mobile stations (MS)

In the case of an ISDN compatible CD 900 network, the first levels of the PSTN and the MSCs become merged to the ISDN to which the BS are linked by 2 Mbit/s trunk interfaces.

In the case of a CD 900 overlay structure the organizational center of the CD 900 is the mobile services switching center which handles the traffic to and from the MS via the BS as well as the interfacing of CD 900 to the PSTN. In this function the MSC is in charge for all call and subscriber specific functions.

For rapid and efficient signalling the CCITT signalling system no. 7 is used exchanging organizational information between the elements of the CD 900 network.

The connection between the network elements and where possible also with the PSTN is formed by PCM 30 basic lines. This permit transmission of 30 traffic channels (TCH) and associated signalling in channel 16 in both directions via a 4-wire connecting line. The information, which may be voice or data transmitted digitally across the radio link BS ◄─► MS therefore gets converted at the BS into the PCM basic format with 32 timeslots per transmission frame (125 µs each) and then transferred to the link/trunk modules in the digital MSC.

CONCLUDING REMARKS

CD 900 is particularly designed to give access to mobile voice and data communication for the general public. To really establish that new service for millions of subscribers per network, it has to be very economical, efficient and future-safe for the subscriber as well as for the operating organization.

The following CD 900 features underline these statements:

* CD 900 provides up to 60 channels per cell being distributed over 3 sectors flexibly assignable according to traffic situation.
* CD 900 operates with relatively low transmitter powers: BS - 25 W burst peak and MS - 4 W burst peak, the latter resulting in about 100 mW mean power, thus indicating the only reasonable solution for handheld telephones.
* Digital signal processing starting with speech digitization and not ending by digital switching ensures reliable connections between CD 900 network subscribers having a transmission quality as used from fixed nets.
* Low cost are achieved for the MS by the extensive use of VLSI technology due to the digital design.
* Each BS has only one wideband transmitter/receiver for all 60 channels saving cost, floor space, power, air-conditioning etc.
* CD 900 offers a broad and future-oriented spectrum of services, the speech transmission being the most important of them.

With respect to data transmission CD 900 offers excellent features because of its extremely flexible and efficient TDM access procedure and the great reserve of traffic channels per base station. This allows further following data transmission possibilities:

- A transparent channel through the speech digitization device, using currently available modems, is provided.
- A 16 kbit/s data transmission bypassing the vocoding device can be provided.
- Larger data streams can be formed by grouping of timeslots for instance up to 80 kbit/s.

Summing up the following can be stated: CD 900 being a combination of a sophisticated digital mobile radio transmission, ISDN capable digital exchanges and digital transmission systems in the fixed networks is the answer to the PTT's request for an efficient, high performance, low cost and ISDN capable digital mobile commun. system well suited to become the future mobile comm. standard.

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