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5 Research into Performance and Enhancements of Second Generation Systems: GSM and DECT

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5.1 Introduction

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This chapter reports on some of the work carried out in COST-231 with relation to second generation personal communication systems, and specifically GSM and DECT. The performance of basic versions of such systems is relatively well known, and the focus of the work was therefore on advanced features and possible limitations. These topics are of importance not only in relation to the full exploitation of the potential of the systems, but also in terms of possible evolutionary transitions towards the third generation via progressive enhancements of the radio and network performance.

GSM is first considered in the chapter, with full discussion of features such as novel diversity schemes and different frequency hopping strategies, and their effects on radio link performance and system capacity. This is followed by a treatment of DECT which tends to focus on emerging DECT outdoor applications. Among the covered topics are a study of DECT receiver performance, propagation measurements for DECT, new proposals for link enhancement, a report on a field trial, and discussion of DECT network capacity in WPBX and RLL applications.

5.2 On Antenna and Frequency Diversity in GSM

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Antenna diversity is a well-known method to mitigate the effect of multipath fading (refer to Chapter 3 for a general discussion of diversity techniques). Analytical expressions for antenna diversity gains in the presence of Rayleigh fading can be found, for example, in [13,15]. Such analytical results are not directly applicable to the GSM system for several reasons: firstly, the GSM signal has a bandwidth of 200 kHz and for some propagation environments frequency selective fading is introduced. Secondly, the channel coding and interleaving processes reduce the impact of signal fading and furthermore the diversity gain becomes speed dependent for a non-frequency hopping transmission link.

The GSM transmission link can gain from frequency diversity in two ways: the required channel Equaliser [9] can exploit frequency selective fading within the channel bandwidth, and Frequency Hopping (FH) [5] can provide decorrelated fading for successive received bursts. Thanks to the channel coding and interleaving, this fading decorrelation can be converted into a frequency diversity gain for slow moving users.

5.2.1 The GSM Test Profiles

The GSM recommendation specifies test power delay profiles for validation of GSM mobile terminals [9]. The profiles are: Typical Urban (TU), Rural Area (RA), and Hilly Terrain (HT), as shown in Figure 5.1. The profiles were modeled from wideband propagation measurements and are representative of various mobile communication environments [2]. The numerical value *x* after the profile abbreviation determines the simulation speed in km/h, e.g., TU3.

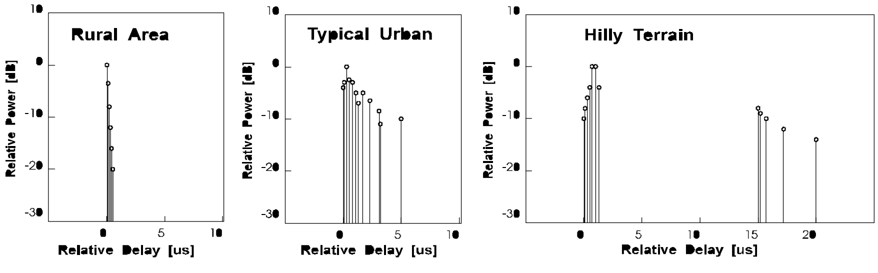

Figure 5.1: GSM specified power delay profiles: Rural Area (RA), Typical Urban (TU) and Hilly Terrain (HT).

The signal strength distribution of the GSM signal exposed to the various test profiles is shown in Figure 5.2. In the GSM context, the RA profile is a narrow-band model, and the small deviation from a Rayleigh distribution is mainly due to a coherent term in the model, which introduces Ricean fading. The TU profile includes considerable time dispersion resulting in frequency selective fading within the GSM bandwidth. The signal strength distribution is therefore significantly improved compared to the Rayleigh distribution. Finally, the time dispersion of the HT profile exceeds the 18.5 μs equalizing window of a typical GSM demodulator[1]. The long time delays mitigate the fading probability, but unfortunately also introduce non-equalisable Inter Symbol Interference (ISI). The signal-strength distribution for the HT profile is therefore not directly related to the received signal quality.

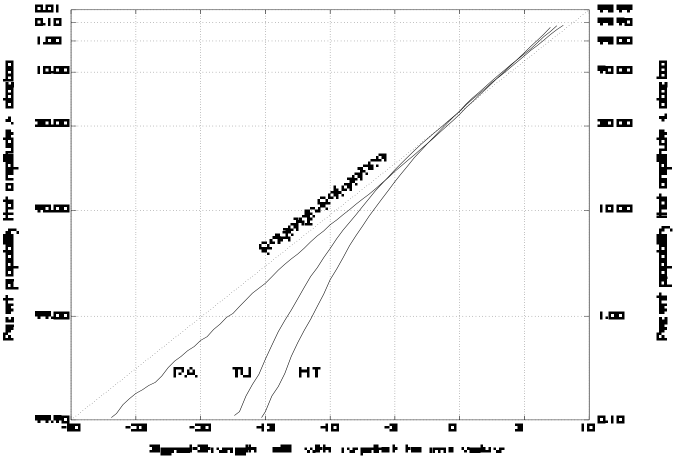

Figure 5.2: Normalized signal-strength distribution for the three GSM specified profiles: Rural Area, Typical Urban, and Hilly Terrain.

It should be noted that these power delay profiles are not suitable for system bandwidths beyond approximately 1-2 MHz, and are therefore inappropriate for simulating non-ideal frequency hopping in GSM. Ideal frequency hopping will be applied in the analysis of FH, i.e., uncorrelated fading between hopping radio channels. This assumption requires in practice a channel separation of approx. 400-600 kHz for urban environments [3].

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[1] A 16 state Viterbi algorithm can cope with time dispersion up to approx. 18.5 μs

5.2.2 The GSM TCH/FS Transmission Mode

GSM specifies a variety of transmission modes on the Traffic Channel (TCH). These modes are :

- TCH/FS, TCH/F9.6, TCH/F4.8, TCH/F2.4 are the transmission modes over a TCH/F (Traffic CHannel/Full rate), respectively for full rate speech, 9.6 kbit/s, 4.8 kbit/s, and 2.4 kbit/s data rates.
- TCH/HS, TCH/H4.8, TCH/H2.4 are the transmission modes over a TCH/H (Traffic CHannel/half rate), respectively for half rate speech, 4.8 kbit/s, and 2.4 kbit/s data rates.

The various transmission modes differ in the details of error correction and error detection (coding and interleaving) schemes [5,6]. Additionally, the control and common channels again use other channel encoding schemes. The performance of the transmission link and the obtainable frequency and antenna diversity gain are dependent on the actual transmission mode. *Only the GSM transmission mode for full rate speech, TCH/FS will be considered in the analysis.* A diagram of the GSM transmission and receiving path for the TCH/FS mode is given in Figure 5.3.

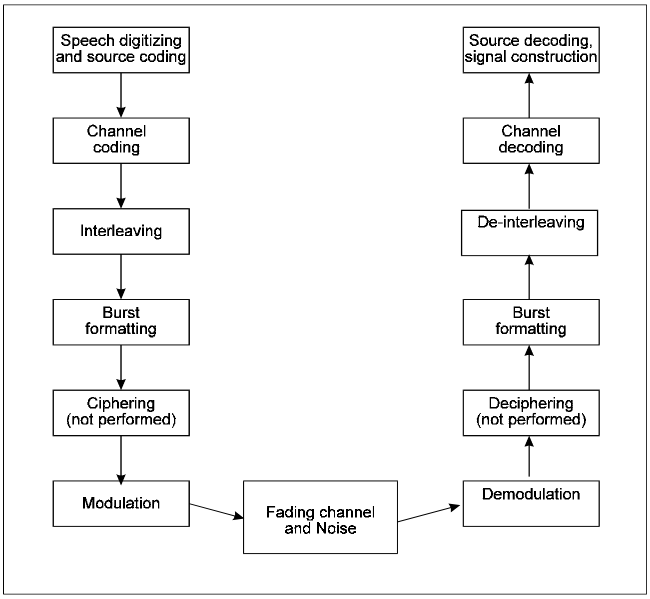

Figure 5.3: Schematic flow diagram of the TCH/FS transmission and receiving path.

The full rate *speech encoder* delivers a data block of 260 bits for every 20 ms (i.e. a net bit rate of 13 kbit/s). The bits produced by the speech encoder are divided into classes according to importance (Classes 1a, 1b, and 2, in order of decreasing importance). The Class 2 bits have only a small impact on the received speech quality, and are often disregarded in signal quality analysis.

The process of *channel encoding* increases the bit rate by introducing redundancy into the transmission flow. For the TCH/FS mode, a 3 bit CRC is firstly applied to the 50 Class 1a bits. This field is used for frame erasure detection at the receive end. Secondly, all class 1 bits are convolutionally encoded (Code rate = 1/2, Constraint length = 5), whilst class 2 bits remain unprotected. The channel encoding produces a data-block of 456 bits, which corresponds to a gross bit rate of 22.8 kbit/s. The *reordering and interleaving* process mixes the 456 encoded bits and sub-groups them into 8 half-bursts of 57 bits, which are transmitted on 8 successive bursts, i.e. an interleaving depth of 8 [6].

The errored bits tend to appear in “faded” bursts, but convolutional codes perform better when errors are randomly positioned. The reordering and interleaving in the GSM signal transmission flow randomize the error events, provided the 8 successive bursts carrying an encoded data block are exposed to decorrelated fading. This requirement can be ensured by either a spatial movement of the mobile station or a change in frequency (i.e. frequency hopping).

5.2.3 GSM Link Tests

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In the pre-operational phase of GSM, reliable link performance test equipment was not available. Furthermore, statistically based hardware simulators cannot cater for the specific propagation conditions experienced in the field. For this reason, measurements were carried out by various groups together with software modem implementation (stored channel simulation) [7,8,55]. In [8,55] the GSM transmission was simulated whereas in [7] a GSM superframe generator was used to transmit ‘live’ GSM data over the network.

As expected, GSM link performance was found to be better correlated with the delay window based W9 and Q16 parameters (see chapter 2) than with delay spread, due to the finite equalisation capability of real GSM receivers. For each modem implementation, a signature surface (link performance level) can be spanned by CNR and Q16 (or W9) [7,55]. This provides a simple means to gain a basic GSM link performance estimate directly from radio channel parameters, and in addition it enables reuse of radio channel measurements, avoiding time consuming simulations.

As an example of results obtained, it was concluded in [7] that GSM coverage could not be provided in areas surrounding fjords by using mountains as passive reflectors (as is done with NMT900). This implies that approximately twice the number of base stations would be required for GSM in mountainous terrain.

With the expansion of fully operational GSM networks, interest has turned to performance enhancement techniques (covered in the remainder of this chapter), and to its use in special environments and applications (e.g. high speed trains - see section 4.8.4).

5.2.4 Frequency Diversity

The activation of slow Frequency Hopping (FH) in GSM offers two advantages:

- *Frequency diversity*: Improved burst decorrelation for slow moving users.
- *Interference diversity*: Interference averaging in the network

Only the improvement from frequency diversity is considered here; interference diversity will be discussed later in the chapter.

Power Envelope Correlation. A power envelope correlation coefficient below 0.7 is often used as a criterion for diversity applications [13]. Assuming that this coefficient is given by $J_0^2(\beta vt)$ [13], then it can be found that the speed of a mobile station must exceed approximately 35 km/h in order to meet the above criterion between two successive received bursts. The frequency diversity gain from FH is thus most essential for mobile station speeds much lower than 35 km/h, i.e. pedestrian speed. The frequency diversity gain from FH will be marginal for high speed mobile stations, because the required decorrelation is obtained through spatial movement.

GSM Hopping Sequences. Distinct *cyclic* and *random* modes of frequency hopping are specified in GSM [5]. The random mode provides both frequency and interference diversity, whereas sequential hopping can only provide frequency diversity. The maximum number of frequencies, $N_{max,}$ that can be used in the hopping sequence is 63 [5]. However, in practice, the number of hopping frequencies N will be much lower because of the limited allocated spectrum and the necessary frequency reuse scheme of a cellular network. For GSM BTS equipment which does not support synthesized frequency hopping, the frequency hopping is performed at baseband, and thus *N* will be limited to the number of installed TRX's.

In cyclic mode, the maximum frequency diversity gain is achieved for N ≥ 8 (determined by the interleaving depth). For small values of N, cyclic hopping provides a noticeably higher frequency diversity gain than random hopping. This is because, for the random hopping case, the probability of using a radio frequency channel more often than 8/*N* times within the interleaving depth of 8 is high, and thus the fading decorrelation within a speech-frame is not optimal.

Frequency Hopping Results. The performance of both random and cyclic frequency hopping has been simulated for a range of values of *N*, from 1 (no hopping) up to 12 [16].

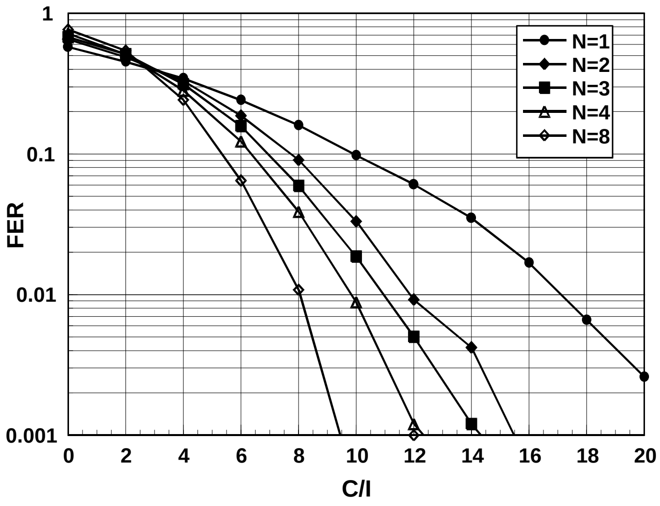

Fig. 5.4: FER (Frame Erasure Rate) as a function of C/I for Cyclic Frequency Hopping, (*N* is the number of frequencies in the hopping sequence)

Fig. 5.4 shows the results for the case of cyclic hopping and the TU3 test condition. It can be observed that the frequency diversity gain is considerable (about 8 dB for *N* = 8 at a FER of 2 %). Even for a low number of hopping frequencies (N ≥ 2), the gain from FH is significant for this test condition. Random hopping gives approx. 1-2 dB lower gain than cyclic hopping for low values of *N* [16]. However, random hopping may still provide the best overall network performance once the improvement from interference diversity is taken into account [30,12].

In Table 5.1, the results for cyclic frequency hopping for the case of co-channel interference are given for both TU3 and TU50. As expected, the frequency diversity gain from FH is modest for the TU50 test condition; the gain is only of the order of 1-2 dB. From the Table, it can be observed that the absolute performances for the TU3 and TU50 test conditions are almost identical, once ideal frequency hopping is applied ($N = 8$).

	TU50: C/I at FER= 2 %		TU3: C/I at FER= 2 %	
No of hopping frequencies	Absolute level [dB]	Relative gain [dB]	Absolute level [dB]	Relative gain [dB]
1	10.0	0.0	15.5	0.0
2	9.0	1.0	11.0	4.5
3	9.0	1.0	10.0	5.5
4	8.5	1.5	9.0	6.5
8	8.0	2.0	7.3	8.2

Table 5.1: Simulation results for Cyclic Frequency Hopping with N = 8 under co-channel interference [9].

5.2.5 Antenna Diversity

The radio link power budget in GSM typically favours the up-link. For cell range extension (and in order to reduce the power budget imbalance), it is desirable to install antenna diversity at the base stations for up-link reception. Downlink antenna diversity may also be required for capacity enhancement, and may be implemented as either Tx diversity (installed at the BTS) or Rx diversity (installed at the Mobile Station). Alternative implementations of antenna diversity in GSM have been studied [17,19,21,22] (see also Chapter 3 for a broader discussion of diversity techniques).

Up-link Diversity Schemes for GSM. The additional cost of antenna diversity at the base station is not critical (both in terms of equipment and power consumption). However classical combining techniques are not suitable due to the frequency selective nature of the channel. Two possible schemes for diversity combining at the base station are described below.

Matched Filter Combining is a pre-detection scheme [17], which is a simple implementation of *Wideband Maximal-Ratio combining*. The GSM demodulator unit estimates the radio channels' impulse responses from the training sequence, and the received signals are matched filtered before detection. Individual matched filtering of each diversity branch co-phases the diversity signals. After the matched filters, the signals can be directly combined and passed to the data-detector, see Fig. 5.5. The combining operation can use weighting coefficients derived from knowledge of the channel conditions (see e.g. [20]).

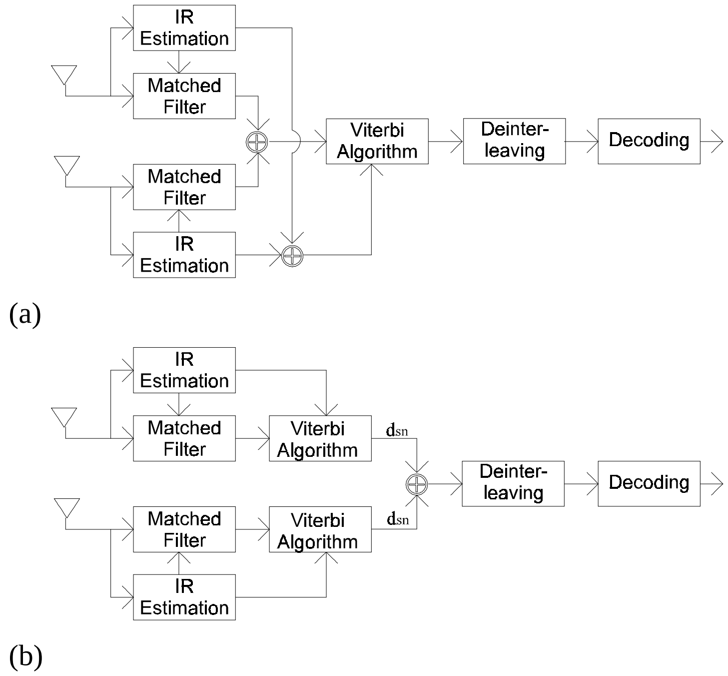

Fig. 5.5: Block diagram of: (a) matched filter combining and (b) soft decision combining.

Soft Decision Combining is a post-detection implementation of Maximal-Ratio combining. An independent data detection is performed for each diversity branch, and the soft decision outputs are combined and passed to the channel decoding unit [17].

The two proposed combining schemes for GSM have nearly equal performance, and the choice will depend on implementation issues. Matched Filter combining gives about 0.3 dB gain over Soft Decision combining under noise conditions, whereas Soft Decision has an advantage of about 0.3 dB in the case of co-channel interference [23].

Downlink Antenna Diversity Schemes. The above combining schemes are not suitable for a mobile station because they demand two parallel RF receiving chains. Two sub-optimal but simple diversity schemes for downlink antenna diversity have been proposed:

- Rx Diversity: Pre-Selection diversity
- Tx Diversity: Delayed signal combining

Pre-Selection Diversity

Switching and Pre-Selection [13,15] is a simple diversity algorithm which is in general applicable to low cost TDMA radio equipment because it requires one RF receiver chain only. Such a scheme may be based on power measurements of the previous received burst(s) or the previous burst in the TDMA frame structure. However, this requires a high degree of envelope power correlation, and this condition will not be fulfilled in GSM for a fast moving MS or in a Frequency Hopping GSM network[2]. This issue excludes also the feedback type of diversity implementations [13,15].

For Pre-Selection diversity implementation in GSM, the signal strength can be measured during the leading part of each received burst. Unfortunately, the GSM burst structure does not contain an initial preamble field prior to the data bits (as in DECT), which might have been used for measuring signal strength. However, it has been found that the corruption of the first few bits in each burst only introduces a degradation of the order of 0.5-1 dB [22]. These bits may therefore be used for signal strength monitoring, since the degradation is much smaller than the diversity gain of “true” Selection diversity.

Such a “destructive” pre-selection diversity scheme has been proposed and analyzed in [22].The optimum period *k* for signal-strength estimation has been found to be 3-5 bit periods, and the switching and receiver settling time *m* has been assumed to be 3 bit periods (see Fig. 5.6).

When the first observed diversity antenna is selected 2* (k+m) bits are corrupted, whereas only (k+m) bits are corrupted if the last observed antenna branch is selected.

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[2] With the exception of mobiles on the BCCH carrier, where the previous timeslot in the TDMA-frame can be used for diversity measurements.

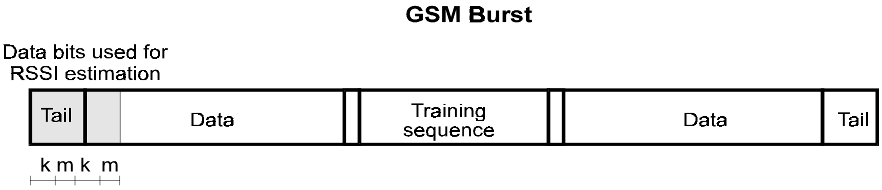

Fig. 5.6: A GSM normal burst with indication of the signal-strength measurement period *k* and the switching time *m*

Delayed Signal Transmission

Antenna diversity has not been implemented in GSM mobile stations until now. However, a Delayed Signal transmission scheme for the down-link path is possible, with simultaneous transmission from a second antenna branch at the base station, and where the relative transmission delay of the second branch is of the order of 2 bit periods [17,18]. The received signal at the mobile station comprises two decorrelated signals with a time delay offset (see Fig. 5.7). These signals are coherently combined by the equaliser, thus reducing the fading probability.

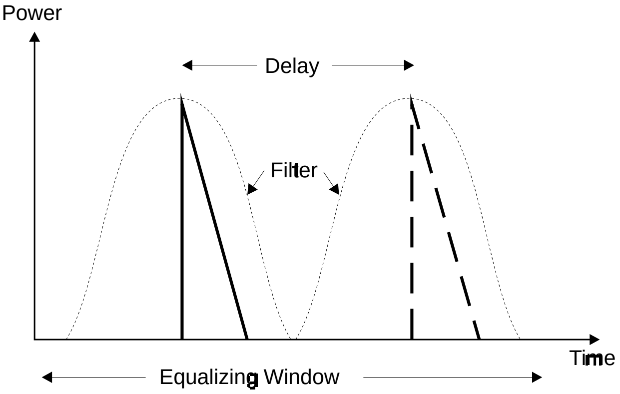

Fig. 5.7: Delayed signal combining of GSM signals

5.2.6 Antenna Diversity Performance Results

Fig. 5.8 and Fig. 5.9 show simulation results for the different antenna diversity implementations in terms of Frame Erasure Rate (FER) and raw (class 2) BER, respectively.

It can be seen from these that the potential gain from two branch antenna diversity in GSM is very high under the conditions given. The figures also illustrate the complexity of antenna diversity evaluation for GSM: the raw performance of Pre-Selection diversity is worse than that of a single antenna at high C/I levels (Fig. 5.9), but its FER performance approaches that of “true” Selection diversity (Fig. 5.8). The distribution of bit errors before channel decoding strongly affects the FER performance, and thus the raw BER is not a good measure of the received signal quality. This is analogous to the case of frequency diversity and FH (FH does not improve the raw BER but nevertheless significantly reduces the FER).

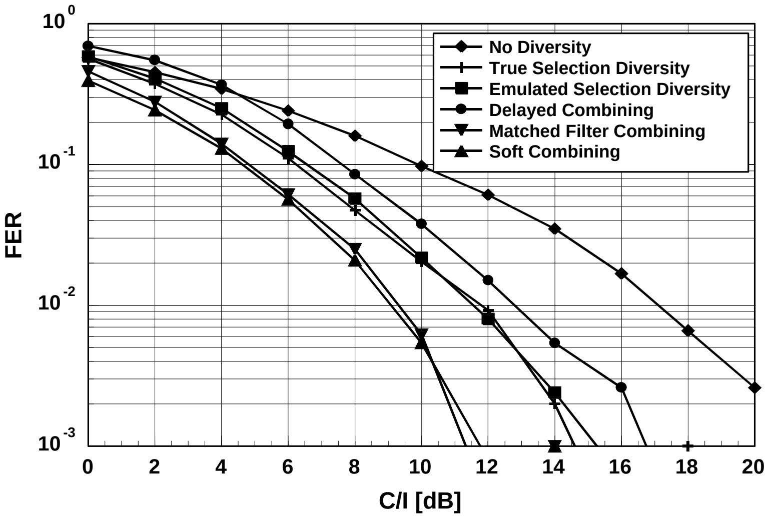

Fig. 5.8: Simulated antenna diversity gain for various diversity algorithms (TU3, no FH, and co-channel interference) [23]

The antenna diversity gain is shown in Table 5.2 for both ideal FH and no hopping. In the latter case, all diversity schemes provide gains (4-7 dB). When ideal FH is used, the antenna diversity gains are reduced by 3-3.5 dB, and only the Maximal-Ratio type of combining schemes (MF and Soft-Decision combining) show a diversity gain exceeding 3 dB.

	TU3 (No FH)		TU3 (Ideal FH)	
No Diversity	15.5	(0.0)	7.3	(0.0)
Delayed Combining	11.3	(4.2)	6.8	(0.5)
Emulated Selection	10.2	(5.3)	6.2	(1.1)
True Selection	10.0	(5.5)	5.2	(2.1)
MF Combining	8.3	(7.2)	4.0	(3.3)
Soft Combining	8.0	(7.5)	3.2	(4.1)

Table 5.2: Required C/I [dB] for a FER of 2 percent for different antenna diversity techniques. The antenna diversity gain [dB] is shown in brackets [23].

Table 5.3 shows antenna diversity performance in noise conditions for TU3, RA250 and HT100. The diversity gain is high for the case of TU3 and no FH, but is lower than 3-4 dB for all other test conditions.

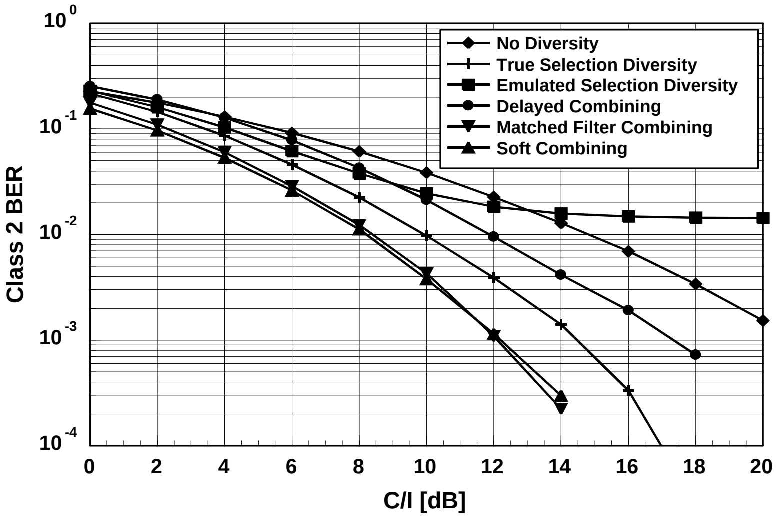

Fig. 5.9: Simulated antenna diversity gain for various diversity algorithms (TU3, no FH, and co-channel interference) [23]

	TU3 (No FH)		TU3 (Ideal FH)		RA250 (No FH)		HT100 (No FH)	
No Diversity	12.5	(0.0)	5.5	(0.0)	5.9	(0.0)	6.9	(0.0)
Delayed Combining	9.4	(3.1)	5.2	(0.3)	5.3	(0.6)	8.2	(-1.3)
Emulated Selection	8.2	(4.3)	3.6	(1.9)	4.0	(1.9)	5.0	(1.9)
True Selection	7.2	(5.3)	2.5	(3.0)	3.2	(2.7)	3.5	(3.4)
MF Combining	5.8	(6.7)	1.6	(3.9)	1.1	(4.8)	2.1	(4.8)
Soft Combining	5.9	(6.6)	1.8	(3.7)	1.1	(4.8)	2.1	(4.8)

Table 5.3: Required Eb/No [dB] for a FER of 2 percent for different antenna diversity techniques. The antenna diversity gain [dB] is shown in brackets [23].

5.3 Capacity Study of a Frequency Hopping GSM Network

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This section discusses capacity improvement in a GSM network through the use of random FH combined with fractional network loading. In general, two strategies can be used for increasing the capacity of such a network:

- Increased capacity per cell
- Reduced cell size (deploying additional base stations)

These two strategies do not exclude each other. Cell size reduction on its own can be very effective since the GSM cell area can vary from more than 100 km^2 to under a tenth of a km^2. No other capacity enhancing methods can provide such a range of more than 3 decades. However, the introduction of micro-cells has some drawbacks in terms of network cost and management.

On the other hand, the combination of Frequency Hopping with RF power control and DTX can provide an increased capacity per cell. When further combined with adaptive antennas, the potential for increased capacity becomes very significant, as will be seen later.

5.3.1 Conventional Fixed Frequency Reuse Schemes

The frequency re-use factor K is given by K = k / n, where k is the ideal cluster size (number of base sites), and n is the number of frequency sets used in a cluster, e.g., for k = 3, K = 3/3 and K = 3/9 respectively represent omni-directional and 120° sectorised BTS configurations.

The BCCH Carrier. The frequency reuse for the BCCH carrier (the beacon frequency) is relatively poor, since the BTS must transmit continuously in all timeslots without RF power control. The most efficient reuse has been found to be when K = 4/12 (for 10 % outage at a CIR threshold of 9 dB) [14]. However, this result is based on a ‘regular’ network layout and a simple pathloss model, and may therefore be slightly optimistic. However, for a sectorised BTS, there is a large step between the cluster size 4/12 and the next value of 7/21 (requiring 75 % more frequency channels). A more flexible frequency reuse method is based on the so called *co-channel interference matrix*, whereby the actual BTS location and configuration are taken into account. A reuse scheme using a pool of 14-18 frequencies for the BCCH carriers is often employed in conjunction with the co-channel interference matrix method [27].

The Traffic Carriers. With non-hopping Traffic (TCH) carriers, the frequency reuse is very similar to that of the BCCH carrier. Even when the

GSM capacity enhancing features (DTX and RF power control) are activated, the capacity improvement is modest without random FH. The frequency reuse for the TCH carrier requires typically a pool of 12-14 channel sets [14,27]. It should be noted that the co-channel interference matrix method allows joint frequency assignment for both BCCH and TCH carriers from a common frequency pool.

5.3.2 Frequency Reuse on Hopping TCH Carriers

When random frequency hopping is activated, a conventional frequency reuse scheme based on a worst case interference situation (i.e. 100 % load) is spectrally inefficient [1,29]. Congestion (hard-blocking) limits the capacity of the network well before the CIR values (soft-blocking) become crucial, since random FH provides both frequency and interference diversity. For the case of full rate speech (TCH/FS), the interference varies[3] over the interleaving period of 8 bursts. The mean co-channel interference level in the network can be adjusted by two parameters:

- The frequency reuse factor, *K*
- The mean fractional loading, *F*

Fractional loading is the percentage *F* of the available channels in the network that may be in use simultaneously (e.g. a fractional loading of 25 % reduces the mean interference level by 6 dB). It is apparent that the two parameters *K* and *F* interact closely: the higher reuse factor *K*, the higher the fractional loading *F* and vice-versa. The advantages of random FH combined with fractional loading can be seen from the following:

- Interference diversity (averaging): all users will be heard nearly equally as interference and therefore a higher mean interference level in the network will be accepted.
- Therefore a low frequency reuse scheme can be combined with fractional loading. The increased number of channels per cell reduces the hard-blocking probability significantly.

5.3.3 Impact of Allocated Frequency Spectrum

Many GSM network operators have been allocated a narrow frequency band. In Table 5.4 the number of available traffic carriers (TCH) is shown

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[3] The interference is not truly averaged as in DS-CDMA

for various frequency bandwidth allocations. It can be observed that the first 2.6 MHz of spectrum (including a guard-band channel) only covers the basic BCCH carrier requirement. For a conventional non-hopping GSM network, the TCH carriers also require 12 frequency channels for a sectorised configuration [1,14]. The number of TCH carriers per cell is thus modest for narrow spectrum allocations, see Table 5.4.

Allocated Spectrum	5.0 MHz	9.8 MHz	17.0 MHz
No of RF carriers	24	48	84
No of BCCH carriers	12	12	12
No of TCH carriers	12	36	72
TCH carrier per cell:			
K = 1/1	12	36	72
K = 1/3	4	12	24
K = 3/9	1.3	4	8
K = 4/12	1	3	6

Table 5.4: The number of available TCH carriers per cell for various spectrum allocations and frequency reuse factors

Table 5.5 shows the maximum relative load of a cell due to blocking, for various numbers of carriers per cell. It can be seen that 4-6 carriers per cell are required in order to achieve a high spectral efficiency. Additional TCH carriers only give a marginal improvement in spectral efficiency (e.g. Erlang/MHz). From Table 5.4 and Table 5.5 it can be concluded that from a hard-blocking perspective, the best frequency reuse schemes are K = 1/1 or 1/3, especially when the allocated spectrum is less than 10 MHz, whereas for large bandwidth not much can be gained by increasing K beyond 3/9. The penalty of a low frequency reuse scheme is obviously higher co-channel interference, which must be compensated for by having the network fractionally loaded.

The optimum solution to the two divergent limitation factors of hard blocking (dismissed calls) and soft blocking (low CIR) can be found by simultaneously optimizing the frequency reuse, *K*, and the fractional loading, *F*. This has been examined via computer simulations [1,14].

Carriers	TCH/F Channels	Erlang B (2 % blocking)	Relative mean load of TCH	Spectral Efficiency
1+1	8+6	8.2	59 %	51 %
2+1	16+6	14.9	68 %	62 %
3+1	24+6	21.9	73 %	68 %
4+1	32+5	27.3	74 %	68 %
6+1	48+5	43.1	81 %	77 %
8+1	72+4	64.9	85 %	81 %
12+1	96+4	88.0	88 %	85 %

Table 5.5: Maximum relative load of a GSM cell at a 2 % hard-blocking level

5.3.4 Results From GSM Network Simulations

Network level simulations of a GSM system have been made in order to investigate DTX, RF power control, random FH, frequency reuse, and fractional loading. The impact of the propagation parameters such as path-loss slope, standard deviation of shadow fading, radiation pattern of the base station antenna and back scattering have also been investigated [14].

Table 5.6 summarizes some of the essential parameters used in the capacity study (for more details see [14,29]). It can be seen that one of the two network performance criteria is the call dismissal probability of 2 % (hard-blocking). The second criterion is based on the fact that 90 percent coverage probability is usually accepted in a GSM network [1]. Hence, if co-channel interference is the dominant quality limitation, it is expected that the network quality will be acceptable if no more than 10 percent of the CIR values are below 9 dB. It should be noted that both the selected threshold values have a strong influence on the achieved capacity.

Path loss	$L_p = 35 \log d$
Log-normal fading standard deviation	6 dB
Correlation distance	1/e at 110 m
Call mean hold time	100 s
Mobile velocity	50 km/h
Cell radius	2 km
Antennas	90 ° sectorised
Allocated spectrum	9.8 MHz
Frequency hopping algorithm	random hopping
DTX factor	0.5
CIR threshold	9 dB with a 90 % probability
Blocking	Erlang B, 2%

Table 5.6: The parameters of the GSM network simulation

Random Frequency Hopping. Random frequency hopping leads to an averaging of the interfering signals. For illustration, Fig. 5.10 shows the CIR of two mobiles using random and no hopping (both without DTX). It can be observed that, without random FH, the signal quality (CIR) is only affected by the shadow fading, which is updated every 0.48 s within the simulation.

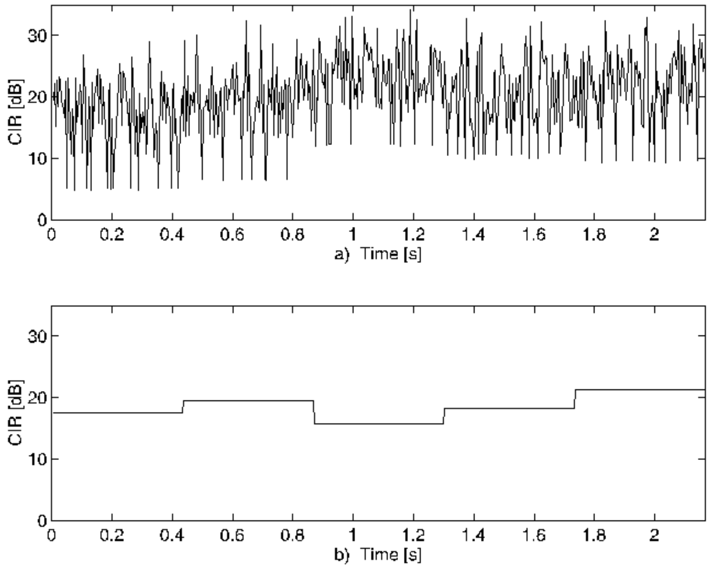

Fig. 5.10: The instantaneous CIR of two mobiles during a period of 520 bursts: a) is with random frequency hopping and b) is without frequency hopping [29]

The interference level on each individual channel changes very slowly and depends effectively on whether a strong interfering signal is present or not on the specific channel. Conversely, when random frequency hopping is activated, the interfering conditions change for each burst. Under such conditions, the average received CIR becomes critical, rather than the worst case situation. The interference reduction from RF-power control and DTX can then be directly translated into a capacity increase, since the improvement is averaged among all mobiles in the network. Without random FH the improvement in mean CIR will not directly translate into a capacity increase since the Mobile Stations will benefit differently.

Impact of DTX and Fractional Loading. The results from the simulation of DTX showed a linear proportionality between the DTX factor and the CIR improvement (i.e., decreasing the DTX factor to 0.5 leads to an interference reduction of 3 dB). The same proportionality holds for the fractional load *F*: a reduction in traffic load by a factor of 2 reduces the mean interference level by 3 dB. These results are as expected and confirm that DTX and fractional loading are very powerful means to reduce the mean interference level in a random hopping GSM network.

Relation Between Reuse Factor and Fractional Loading. From a hard-blocking perspective a low reuse factor *K* is optimal, but the drawback is the higher potential interference level, which demands a low fractional loading *F*. Table 5.7 shows the maximum fractional loading for various reuse factors. The lowest reuse factor that allows full loading is K = 3/9. The maximum fractional loading of 25-30 % for K = 1/3 implies a need for interference reduction of 5-6 dB relative to a fully loaded network.

Reuse factor K	1/1	1/3	3/9	4/12
Maximum load due to interference	6-7 %	25-30 %	100 %	100 %

Table 5.7: The maximum load of a FH GSM network limited by co-channel interference (C/I > 9 dB with 90 % probability)

Maximum Capacity. Various reuse factors and fractional loading values have been simulated in order to determine an optimal network configuration. Maximum capacity has been defined as the smallest load for which one of the blocking criteria is reached. The hard blocking limit depends on the allocated frequency spectrum, and therefore a configuration with 36 TCH carriers (9.8 MHz) is used as an example. Table 5.8 provides the resulting maximum capacity figures.

Random Frequency Hopping			
Reuse	**Erlang/cell**	**Erlang/site**	**Blocking**
1/1	20.2	20.2	Soft
3/3	61.4	61.4	Soft
4/4	60.5	60.5	Hard
1/3	28.8	86.4	Soft
3/9	23.7	71.0	Hard
4/12	16.6	49.7	Hard
Static (no interference diversity)			
Reuse	**Erlang/cell**	**Erlang/site**	**Blocking**
4/12	16.6	49.7	Hard

Table 5.8: Maximum capacity of various reuse factors for a network with 36 TCH carriers (at 2% call congestion and 9 dB C/I with 90 % probability). Note that capacity from the BCCH TCH timeslots is ignored [29].

These results are also illustrated in Fig. 5.11.

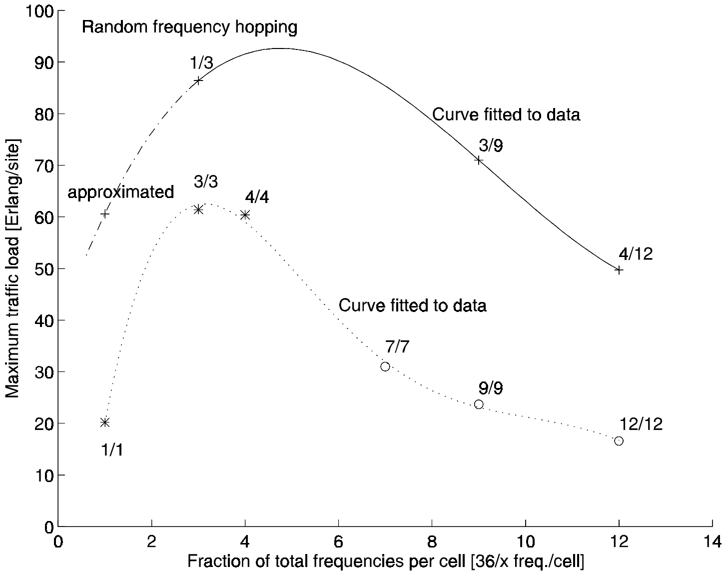

Fig. 5.11: Maximum capacity per site as a function of frequency reuse factor K for a network with 36 TCH carriers (excluding BCCH carrier traffic). The upper curve is for sectored BS sites and the lower one is for omni-directional sites.

The maximum capacity per site is obtained for a sectorised base station and a frequency reuse factor K = 1/3. This result has also been found in [1]. The capacity increase of a random FH network using a frequency reuse scheme of K = 1/3 is approx. 74 % compared to a non FH network with a frequency reuse scheme of K = 4/12. (but in general the capacity increase depends on the spectrum allocation).

In practice, use of the K= 1/3 scheme would make frequency planning trivial. However, a large number of TRXs is required in each site (in the case of baseband hopping), and intelligent radio resource management software must be included in the Base Station Controller for control of fractional network loading.

5.3.5 Interference Gain from Fractional Loading

The capacity study of a random FH GSM network [14] was based on a 9 dB mean CIR threshold. The CIR threshold of 9 dB is determined by link simulations with a continuous co-channel interfering signal according to the test specifications in [9].

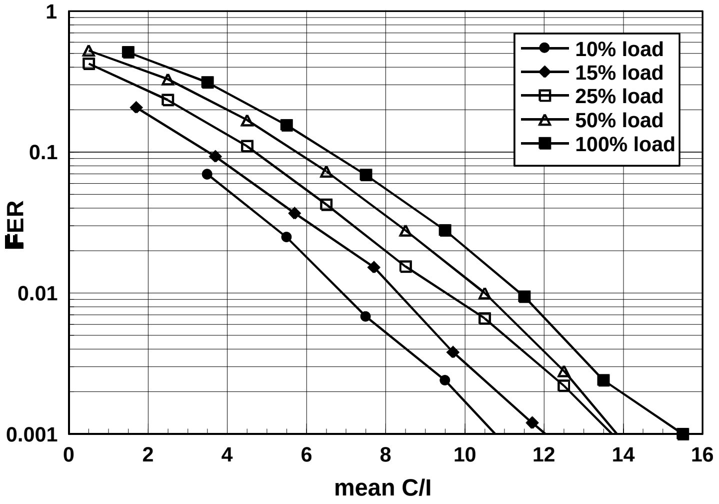

Fig. 5.12: FER as a function of mean CIR for a fractionally loaded network. The load values given are a combination of DTX and fractional network loading [30][4].

However, when using random FH combined with DTX and fractional loading, the co-channel interference pattern will not be continuous, but

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[4] Log-normal fading has been added to the interfering signal.

instead change significantly from burst to burst. Thus, some bursts will be heavily interfered whilst other bursts will be received virtually without any interference. Results from link simulations with such an interference behaviour have shown a significantly reduced Frame Erasure Rate [12,30], compared to the test interference situation specified in GSM 05.05 [16]. For an ideal reuse cluster there will be, on average, 6 equally strong interfering signals [13]. Due to shadow fading, the 6 interferers will have distinct instantaneous levels. In [11] and [30], it has been shown that only one or two of the interferers are usually dominant at a time, and thus the on/off pattern created by DTX and fractional network loading will be reflected in the interference pattern. In Fig. 5.12, the FER is shown as a function of mean CIR for several values of fractional loading. At 15 % load (i.e., 30 % fractional loading and a DTX factor of 0.5), the quality improvement corresponds to about 2-3 dB gain in CIR. However this interference gain from fractional loading cannot be linearly converted into an additional capacity improvement, because the higher fractional loading will decrease the interference gain.

Base Station Synchronization. The results shown above assume an ideally synchronized network. In real life the BTSs in a GSM network are not synchronized, and the relative time alignment of interfering bursts will be random and uniformly distributed. The impact of this has been analyzed in [30]. For the case of 30 % fractional loading and a DTX factor of 0.5, the relative degradation from an unsynchronised network is below 0.5 dB compared to the ideal synchronized case shown above (where the propagation delay is also ignored).

5.3.6 Potential Capacity Gain from Smart Antenna Systems in a K = 1/3 Random FH GSM Network

Recently, interest in smart antenna systems (either adaptive steerable or switched beam antenna arrays) has increased due to their potential for capacity and range enhancement of mobile communications systems.

For a random FH GSM network the frequency reuse factor, *K* can be changed from K = 4/12 to 1/3, which gives the maximum capacity per site. The capacity limitation for the K = 1/3 reuse scheme is CIR outage (soft blocking), and the fractional loading of the network must be kept below 25-30 % (see Table 5.7). By using adaptive antenna arrays to suppress interference, the fractional loading can in theory be increased to the hard-blocking limit. The CIR gain of the antenna array needs to be of the order of 5-6 dB if the system is to reach the load set by hard-blocking.

In [32] the antenna array geometry has been analysed. Simulations which include the effect of angular spreading from the environment indicate that an 8 element (horizontal) linear array meets the CIR requirements. Table 5.9 gives the potential capacity increase of a random FH GSM network using adaptive antennas, assuming that the required CIR gain of about 5-6 dB is achieved.

Frequency reuse Scheme	K = 1/3	K = 4/12
GSM network without adaptive antenna array		
Load limit from Soft-blocking	30 %	100 %
Load limit from Hard-blocking	87 %	69 %
Capacity per site [Erlang]	86.4	49.7
GSM network with ideal adaptive antenna array		
Relative potential capacity gain	2.9	1.0
Capacity per site [Erlang]	250.6	49.7
Capacity increase relative to K=4/12	400 %	0 %

Table 5.9: Potential capacity increase of a random FH GSM network using K=1/3 frequency reuse and adaptive antenna arrays. The hard blocking limit is calculated for 36 TCH carriers (9.8 MHz).

5.4 The DECT Standard

Andreas F. Molisch, Heinz Novak, Josef Fuhl (TU Wien, Austria)

5.4.1 General

The pan-European DECT (Digital Enhanced Cordless Telecommunications) Standard [33,34] enables the deployment of a new generation of cordless telephones and indoor personal communication equipment. DECT specifies the wireless connection set-up and release between fixed base stations and mobile terminals. The mobiles can be cordless telephones or other terminals in a short range private or business indoor environment.

From the user's point of view the most striking change from existing cordless telephones is that one base station can serve multiple mobiles simultaneously. Additionally, in business networks the user is not related to one particular base station, which results in higher accessibility.

The DECT mobile can perform handovers between different base stations of a wireless network as in cellular mobile communication. The difference is that location, coverage range and frequency reuse of the base stations need not be preplanned by a system operator because the system is self organising in its use of spectral resources.

To reduce hardware costs in the base stations accessing multiple mobiles and to minimise management efforts, the DECT standard embodies a change from today’s conceptually simple, analogue FDD/FDMA (Frequency Division Duplex / Frequency Division Multiple Access) to the more complex FDM/TDD/TDMA (Frequency Division Multiplex / Time Division Duplex / Time Division Multiple Access) with digital speech transmission. This means that a number of freely accessible frequency channels are shared by multiple users for both transmission directions.

5.4.2 The DECT Standard and its Challenges

In the DECT standard, the FDM dimension allows access to 10 different frequency channels in the range 1.88 to 1.90 GHz. The TDD format means that each frequency channel has a repetitive frame structure, with each frame having up-link and downlink sections (as shown in Fig. 5.13). In addition, DECT provides 24 slots in each frame, enabling up to 12 users to share a frequency channel in time division multiple access mode. The slots are separated by guard times to ensure that consecutive time slots are not overlapping, for channel switching and TDMA power ramping. A total of 120 logical channels would therefore be available at a single base station if there were no reuse constraints. In practice, a standard DECT base station has a single transceiver and can access only 12 of these simultaneously, so that more than one base station can service a particular area without collision problems. This allows a dense packing of base stations, without defined cell boundaries, resulting in large traffic capacities [35].

As seen in Fig. 5.13, a DECT slot begins with a 16 bit preamble and a 16 bit packet synchronisation word (the 32 bit S-field). This is followed by 64 bits of signalling (A-field), which include a robust Cyclic Redundancy Check (CRC) for the detection of packet reception failures. Finally, the B-field contains 324 bits of data, enabling the transmission of 32 kBit/s ADPCM coded speech using a single slot. The transmission data rate is 1.152 Mbit/s.

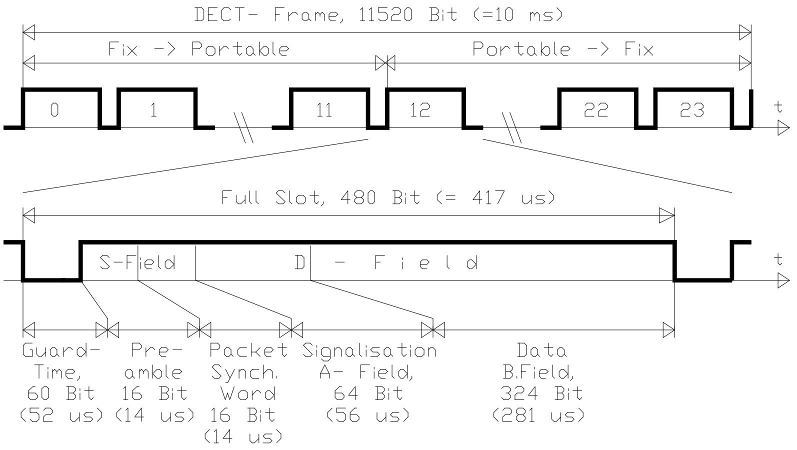

Fig. 5.13: DECT frame and DECT slot structures

DECT uses the well known modulation format GFSK with the moderate BT product of 0.5, which provides a compromise between emitted spectrum and intersymbol interference [36]. The resulting RF-channel bandwidth is about 1.33 R or 1.559 MHz (for a 99% power criterion). With the specified channel spacing of 1.728 MHz (1.5 R), a very significant adjacent channel emission of -40 dBc occurs (in analogue systems this value is normally below -80 dBc). For successful operation of a wireless DECT speech connection, bit error rates below 10^{-3} and slot error rates below 10^{-2} are required. Table 5.10 shows a summary of important DECT parameters.

Transmission Format:	FDM/TDD/TDMA
Frequency Band:	1880 - 19000 MHz
Centre Frequency for Channel N (0..9)	1 897 344 - N * 1 728 kHz
Number of Frequency Channels	10
Channel Spacing:	1.728 MHz
Frame Length (24 Slots):	10 ms
Data Rate:	1.152 Mbit/s
Modulation Method:	GFSK, BT = 0.5
Tolerated Bit Error Rate (*):	$< 10^{-3}$
Tolerated Slot Error Rate:	$< 10^{-2}$

Table 5.10: Important parameters of the DECT standard

(*) for speech service only

The DECT standard does introduce some new technical challenges when compared to classical analogue systems, as listed below [37,38]:

- The dynamic range between consecutive slots can be up to 100 dB due to the absence of power control.
- Due to transmission delays, channel variations, and synchronisation errors, the incoming slots can be asynchronous at bit, slot, and frame level.
- High adjacent channel- and co- channel interference cause conflict situations, leading to a requirement for intracell handover .
- Distributed slot and channel allocation requires intelligent terminals with field strength and signal quality measurement capabilities to estimate, avoid and handle transmission collisions.
- Even in indoor applications, the DECT RF channel suffers from significant dispersion (delay spread).
- The absence of channel coding for error protection (and interleaving) means that terminals must be able to handle error bursts and missing slots.
- FDM/TDMA requires extremely fast switching of synthesisers.
- Additional outdoor and indoor/outdoor applications are envisaged (e.g. public access, radio in the local loop) which may pose further challenges.

5.5 A Physical and Medium Access Layer DECT Testbed

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Several testbeds were developed by participating organisations in COST in order to evaluate the performance of transmission according to the DECT standards. In the following some of the features of these are described.

5.5.1 Modelling of a DECT Wireless Link

The design of a DECT testbed requires the analysis of a realistic DECT wireless link. The slots are transmitted over a fading channel, and both uplink and downlink are interfered by various adjacent- and co-channel signals. The incoming signal at the receiver's antenna is the sum of these signals after convolution with each individual, time variant channel impulse response, as well as white gaussian noise. Disregarding some differences at higher layers of the standard, the DECT link is on average (but not instantaneously) symmetrical, and in practice there is usually one dominant interferer. Therefore it follows that a single transmission direction can be considered, and it is possible to replace the set of interferers by one well defined adjacent- or co-channel transmitter without losing much generality.

Further, a single dispersive fading RF channel is required (for the desired signal). In the case of the interfering signal, it is expected that the small indoor delay spreads will not modify the interfering signal behaviour significantly, and it will be sufficient to implement flat Rayleigh fading.

5.5.2 The DECT Testbed

The basic arrangement of the DECT testbed of [39] is shown in Fig. 5.14. It consists of a unidirectional DECT RF link scenario, including one desired transmitter (TX1), one interfering transmitter (TX2), the receiver (DRX) and an optional channel simulator (CAN). The return link is performed by a wired low data rate signalling connection from the receiver via a controlling personal computer (DTC) back to the desired transmitter (TX1). Transmitted data (D_TX), received data (D_RX) and slot synchronisation information (DV_TX, DV_RX) is transported by a wired high data rate connection to an error counter (ERC).

The error counter has as inputs the delayed data and data-valid signals from the desired transmitter TX1, and the equivalent signals from the DRX. Three statistical parameters are used to quantify the transmission quality in burst mode: the bit error rate (BER), the synchronisation error rate (SER), and the average bit error rate (ABER) [39].

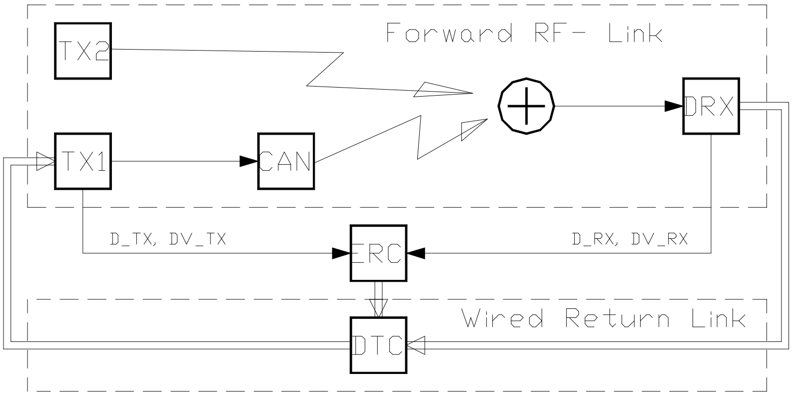


Fig. 5.14: Basic arrangement of the DECT testbed

The channel emulator (CAN) used with this testbed is realised by a tapped delay line with repeater amplifiers which can supply antennas at delays of 0 to 450 ns in steps of 50 ns. The output power of each tap is adjustable in order to select desired power delay profiles, thereby synthesising a particular radio environment. The time variant instantaneous delay profile then results from the natural Rayleigh fading of every discrete delayed path in a low dispersion environment. To provide statistically independent signal paths, the antennas are separated by a distance much greater than the coherence distance of the spatial fading pattern.

Conversely, the DECT testbed of [40,42] has no wired connections, enabling applications and Tx-Rx separations in excess of what is practically possible with a wired approach. It is therefore particularly suitable for outdoor operation and direct testing in dispersive environments. This testbed includes a dual receiver, allowing for live diversity tests. The transmitter and receiver radio parts are built from standard integrated components, and the modems are implemented via DSPs following ADC/DAC at a suitable IF.

5.6 Propagation studies for DECT environments

Andreas F. Molisch, Heinz Novak, Josef Fuhl (TU Wien, Austria)

The performance of DECT strongly depends on the propagation characteristics observed within the deployment area. Channel characteristics experienced under typical operation conditions are therefore of great interest. As discussed later, for satisfactory performance the rms delay spread should not exceed 100ns (without antenna diversity) and could go up to maxima of 250ns and 450ns with, respectively, RSSI and ideal BER driven diversity [47].

The environments may be categorised according to the three different types of DECT system operation [48]:

1) Indoor propagation channel: residential and business cordless telephones applications
2) Indoor/outdoor propagation channel: radio extension of public and private networks
3) Outdoor propagation channel: Telepoint system applications

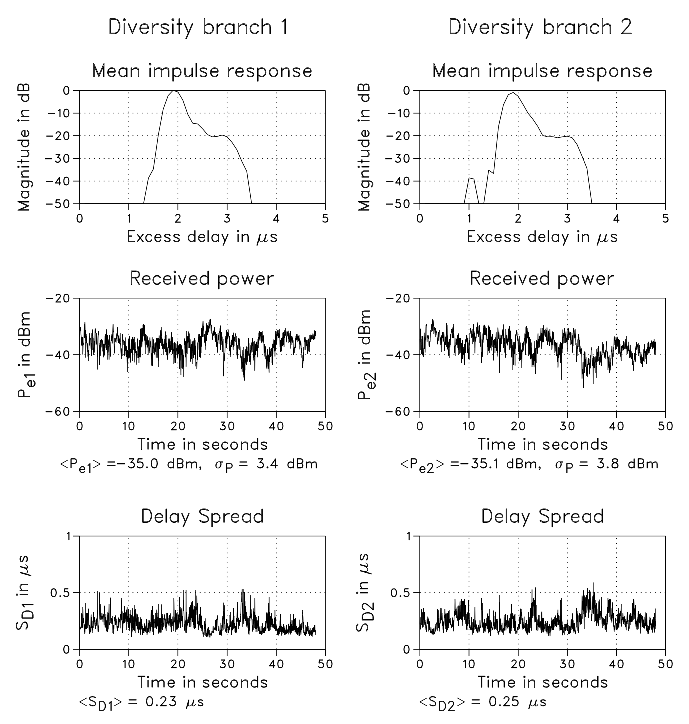
5.6.1 Measurement Results

Narrowband and wideband measurements have been performed in order to assess the performance of a DECT link for the different classes of environments. The main focus was on wideband measurements [49,50,51,53,57,59,58] and specifically on determining delay spread and fading statistics. The results vary in scope due to the different types of environments under consideration.

Reference [48] reported typical values for the delay spread of 11-147ns for environments of category 1, 43-270ns for environments of category 2, and 57-231ns for environments of category 3. When Ricean fading was observed in the measurements the K-factor was usually low (K<2).

Propagation measurements for environments of category 3 (two streets and two city squares of downtown Oslo) were given in [59]. In streets, the mean delay is less than 75ns and the delay spread is less than 63ns at 90% of the measurement locations. However, for squares (whose dimensions are larger), these figures rise to 157ns and 148ns, and the delay spread is less than 100ns in only 55% of the locations.

Tests were carried out in outdoor and indoor Telepoint environments [53] in Aalborg (in a railway station and hardware store respectively). These showed delay spreads up to around 300 ns and corresponding frequency domain magnitude variations V_m [58] around 20 dB (see also chapter 2 regarding this parameter), using antenna BS heights of 4 m. The corresponding average dispersion figures were around 100 ns and 10 dB.



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Correlation of complex narrowband envelope: 0.36

Correlation of narrowband power: 0.23

Correlation of wideband received power: 0.23

Number of analyzed impulse responses: 2000

Number of first plottet impulse response: 1

Fig. 5.15: Measured impulse responses, wideband received power and delay spread in the two diversity branches [57].

Wideband propagation measurements were carried out at the Frankfurt railway station using two diversity branches [57,58,77]. Most of the observed power delay profiles show an exponential decrease, suggesting that the scatterers are located all around the receiver. Maximum excess delays of 3µs and delay spreads up to 200 - 300ns have been observed. The delay spreads are reduced if the base station antennas employ shaped elevation patterns. Fig. 5.15 shows the mean impulse responses, the received power levels and the delay spreads for one such diversity measurement [57]. The power levels and delay spreads of the two branches have the same statistics, but their instantaneous values are distinct.

For two monopole antennas mounted 20cm (1.2λ) away, the correlation coefficient of the wideband received power was less than 0.25, i.e. the two branches can be considered to be uncorrelated.

Finally, measurements reported in [49,50,52] concentrated on street canyons. It was observed that the path loss is reduced with respect to free space loss by a wave guiding gain factor, and that the delay spread tended to be below 90 ns when the transmitter is placed well below rooftop. However, paths with larger delays are observed in roundabouts and street crossings, and, similarly, the delay spread also increases dramatically if the transmitter antenna is placed above rooftop. It was also shown that the dominant propagation paths are the direct LOS path, reflections from the wall of canyons and back reflections from building fronts at the end of the canyon. Besides these deterministic rays which may be derived using ray tracing, additional scattered components were found arising from obstacles which may vary from day to day, and which require a statistical characterisation.

Measurements performed in a typical office area [51] showed that, under indoor LOS conditions, the delay spreads are very small (typically about 25 ns). However, the delay spreads increase by a factor of four when the transmitter is placed in the central court yard and in addition the path loss can increase beyond the DECT limits due to e.g. fire protecting walls.

The measurements quoted suggest that time dispersion could impact system performance for environments types 2 and 3. However, even in these cases, the delay spread values are within a range where diversity and/or equalisation techniques [47] can be successfully employed.

5.6.2 Channel Models

From the measurement results obtained, channel models have been derived for simulation and performance assessment. An example is the set of models in [60], which are all single exponentials with delay spread and maximum excess delay dependent on the type of environment. For type 1 environments, the suggested typical and worst case values are: delay spread 100ns and 200ns, and maximum excess delay 691ns and 1382ns. For types 2 and 3, the delay spread range is 150ns/300ns and the maximum excess delay range is 1036ns/2072ns. The profile taps are Rayleigh fading with a fading rate of 2 Hz for all environments. The most common channel model, however, is the two path channel with equal power in the two paths, although this model is rather simplified [49,60]. Typically, both paths will be Rayleigh-fading. A more appropriate model is a 2-delay exponential decay profile. A simple method for controlling the delay spread for this model in a test site was presented in [61].

5.7 Basic Performance of DECT

Andreas F. Molisch, Heinz Novak, Josef Fuhl (TU Wien, Austria)

In contrast to GSM, DECT does not use an elaborate channel coding scheme, and the speech coding is much simpler (enabling lower production and development costs). As a result, good speech quality can only be achieved with BERs below 10^{-3}. This is therefore the performance threshold that should be achieved by a DECT system in most circumstances. An alternative criterion is a Burst Failure Rate (due to code check failure or lack of synchronisation) below 1%.**Error! Bookmark not defined.**

As any mobile communications system, the BER in DECT is determined mainly by 5 factors: (i) thermal noise (additive white Gaussian noise AWGN), (ii) co-channel interference (CCI), (iii) adjacent channel interference (ACI), (iv) intersymbol interference (ISI), and (v) random FM. However, the relative importance of these factors differs from usual (cellular) systems. Firstly, DECT is intended to operate mostly under conditions of large SNR, particularly in high traffic density areas where base station coverage will overlap, so that SNRs in excess of 30dB can be expected. For GMSK modulation, this implies a BER due to noise smaller than 0.5×10^{-3} (even for a flat Rayleigh fading channel), so that reasonable speech quality can be anticipated in such an environment. Error rates due to co-and adjacent channel interference are also typically small, because of the flexibility in channel assignment, avoiding interfered channels (this may not be the case in an office building where various DECT systems are installed or in cordless PABXs). The random FM is completely negligible because of the high data rate.

A physical process that may strongly constrain the available quality is the time dispersion (frequency selectivity) of the radio channel, which causes intersymbol interference. The resulting errors cannot be decreased by simply increasing the transmitter power, and are thus often called "error floor" or "irreducible errors" (although in a later subsection we will see how these errors can be reduced by diversity or equalisers). In contrast to GSM, the specifications for DECT do not foresee an equaliser (since performance in dispersive channels is not specified), so that DECT may be quite sensitive to time dispersion. Any echo with a delay larger than one bit length will clearly appear as co-channel interference, but even much smaller delays can lead to considerable BERs. This subject has been at the core of much of the DECT research in COST 231, and has led to new insights into the error mechanisms.

The simplest *model* for a DECT system consists of a pure MSK modulator, a GWSSUS channel, and a simple differential detector. Sampling is done either on the first arriving path or on the average mean delay. This system formed the basis of most of the earlier investigations of the error floor, performed using Monte Carlo simulations, measurements, or analytical computations.

(i) Monte Carlo simulations [49,58,60,63] are essentially a straightforward computer implementation of the system, where the statistically changing parameters, such as the channel transfer function, noise samples, etc., are chosen from the appropriate statistical distributions. They are very flexible, and many detailed effects can be implemented and studied.

(ii) Measurements were performed on the DECT testbeds described in the previous section [40,42,64] .

(iii) Analytical investigations were carried out using the group-delay method [65]: the errors are caused by phase distortions, which are in turn related to changes in the group delay occurring in the fading dips. Similar results were also obtained through the *echo* method, and the *correlation matrix* method (more details can be found in Chapter 6).

(iv) Another interpretation of the errors can be given by considering the phasors of the channel impulse response [66]. This method is especially suited for the two-delay channel model, where the impulse response is

$$h(t,\tau)=a_1(t)\times\exp(j\varphi_1)\times\delta(\tau-\tau_1)+a_2(t)\times\exp(j\varphi_2)\times\delta(\tau-\tau_2) \qquad (5.1)$$

where a_1 and a_2 are the statistically distributed amplitudes (e.g. with independent Rayleigh distributions) and φ_1 and φ_2 are the uniformly distributed phase shifts; τ_1 and τ_2 are the delays of the two paths. For such a channel, errors occur if the normalised total phasor $1+\exp[j(\varphi_2-\varphi_1)]\cdot a_2/a_1$ falls into certain "error regions" in the complex plane. These error regions are circles, whose centre co-ordinates and radii depend on $\tau_2-\tau_1$ and the bit combination. The error regions are close to the origin; in other words, errors occur mainly in deep fades (the same result as obtained by the group delay method). The average BER is then the probability that the total phasor falls into the error region, averaged over the statistics of the impulse response. For small delay spreads, a two-delay Rayleigh channel, and sampling at $T_s=(\tau_2-\tau_1)/2$ (i.e. the optimum fixed sampling time), we get the exact result

$$BER=(1/2)\times(\pi/4)^2\times(S/T)^2 \qquad (5.2)$$

The main conclusion from these investigations was that the average BER is approximately $0.5\times(S/T)^2$, where S is the delay spread of the channel, and T the bit length, and that the shape of the delay power profile has very little influence on the BER (less than a factor of 2). The maximum delay spread that still gives tolerable speech quality is of the order of 40-100ns, corresponding to path length differences between 20 and 50m. This can occur easily in larger office buildings, and in outdoor environments. The latter has become of special importance recently, because of increasing interest in the use of DECT for radio in the local loop (RLL) applications [54,59], and for PCS systems.

The errors are also bursty: if the mobile is in a fading dip, then the BER is extremely high (of the order of 25%), otherwise no errors are observed. Such error bursts can be quite long, due to the slow speeds typical of cordless systems, and the fact that the environment in homes and offices is often quite static.

Performance with Adaptive Sampling : The BER can, however, be much improved if burst adaptive sampling is used in the model [67]. The ISI often distorts the eye pattern in such a way that, whilst there is a residual opening, the position of this opening changes with the instantaneous channel constellation. With adaptive sampling, it is possible to follow the most *open* position of the eye, while for fixed sampling, the sampling instant may lie inside an eye closure region.

For the case of pure MSK without receiver filtering, adaptive sampling leads to a complete elimination of the error floor. Depending on the channel constellation, the optimum sampling time is at the mean excess delay plus/minus one half the bit length (where the eye will be open). In an actual DECT system, however, the data sequence is filtered to make the spectrum narrower (i.e. GMSK is used), and the received signal is filtered in order to reduce noise. These filtering processes lead to a *smearing* of the bit transitions, and to further closure of the eye. In this case, complete elimination of the error floor is not possible, and the BER (due to ISI) is of the form $k*(S/T)^2$, where k is a constant which depends on the filter width [68]. BER computations can be done efficiently for a two-path model, by using a generalised definition of the *error region concept*: these comprise all channel constellations that lead to errors regardless of the sampling time.

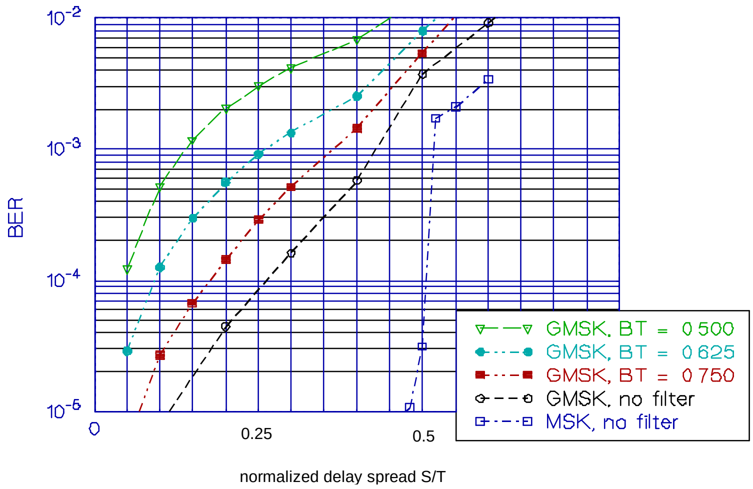


Fig. 5.16: Error floor with adaptive sampling

Fig. 5.16 shows the computed BER floor using near-optimum adaptive sampling (exhaustive search of sampling point using 16 times oversampling). Most striking about the figure is the dependency of the results (e.g. delay spread for BER of 10^{-3}) on the modulation scheme and receiver filter bandwidth. For example, increasing the single sided bandwidth by 50% more than doubles the delay spread range. In terms of absolute performance, the figure predicts that delay spreads of 0.14-0.26 T (i.e. 120-225 ns) could theoretically be achieved whilst using the range of IF filter bandwidths typical of DECT. However this assumes perfect synchronisation to sometimes negligibly small eye openings, no phase distortion in the receiver filter, perfect frequency synchronisation, and an ideal differential phase detector. In practice a limit of around 100 ns is more realistic.

The determination of the optimum (adaptive) sampling time is thus a matter of considerable importance for performance optimisation of DECT in dispersive channels. One possible method is to use a metric based on the size and length of the eye opening [69]: if the eye is open in several regions, then the middle of the region with the longest opening is chosen as the sampling time. Another possibility is the explicit use of the DECT preamble, which is known to the receiver. It is possible to make an N-fold oversampling of the received signal, correlating it with the transmitted sequence, and search for the maximum correlation point. The optimum sampling time can only be found if noise is negligible, and infinitely high oversampling used. However, numerical computations have shown that N=4 or N=8 give results that hardly differ from very large oversampling.

5.8 DECT Radio Performance Enhancement

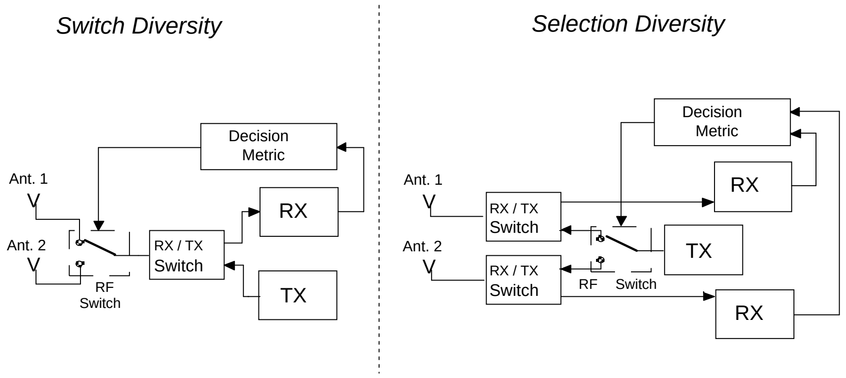
Luis Lopes (University of Leeds, UK)

The above discussion has concluded that there are some environments (particularly some of type 2 and 3) where the performance of the *basic DECT receiver* (i.e. standard limiter discriminator or phase detector without diversity) will be degraded by time dispersion. DECT however is a flexible standard enabling the integration of additional performance enhancement features as a function of cost and performance requirements. Specifically, it is possible for manufacturers to deploy a large variety of different spatial diversity techniques or channel equalisation **-** but none of these is demanded or constrained by the standard. In the following, a number of novel proposals developed during the course of the project will be discussed.

5.8.1 Standard Spatial Diversity: Switch and Selection Techniques

In general, it is envisaged that some form of diversity should be provided at the base station only, most commonly by using two antennas. Antenna combining has been only briefly considered [53,70], and most proposed arrangements use some form of switch or selection, as illustrated in Fig. 5.17.

In *switch diversity*, a metric is computed at the base station on reception of each burst; this metric could be simply the RSSI or the CRC check, or another parameter. Using this metric, a decision is made as to which antenna to use for transmission, as well as for the next reception. In *selection diversity*, two parallel receiver chains are provided such that two metrics can be computed. Typically, antenna selection on the up-link would be made *after detection*, on observation of the CRC check and RSSI, and the chosen antenna retained for the downlink.



Decision Metric : RSSI, CRC Check , etc.

Fig. 5.17: Switch and selection diversity configurations

The implementation variables are therefore the quality metric and the configuration. If the channel is static (no movement of either environment or portables) and the only impairment is low signal level, then there will be minimal performance differences resulting from these variables. This situation is however untypical of real cordless environments which can display both continuous and bursty channel variations, and suffer from interference (and in some cases from time dispersion).

The best theoretical performance from a dual antenna arrangement is achieved when knowledge of errors at both antennas is available. Under both noise and interference conditions, a gain of about 10 dB is then obtained under Rayleigh fading at the target BER or BFR (Burst Failure Rate). For time dispersive conditions, the error region method previously discussed can also be used to compute this performance limit. In this case, errors occur if the total phasors of both diversity branches fall into an error region, and it is found that the error floor is much smaller for low delay spreads but increases with $(S/T)^4$. The theoretical maximum delay spread would again be a function of the IF filter, but is typically in excess of 400 ns.

Typical BFR performances of selection diversity schemes based on CRC and RSSI are shown in Fig. 5.18, for a delay spread of 200ns [40]. As expected, the performance of a standard detector is not acceptable even at high values of Eb/No. RSSI selection diversity provides some gain but still has a very marginal performance; and finally CRC selection is clearly superior (although it still loses a few dB with respect to a flat fading channel). Similar results have been obtained by other studies [60,62,63]; for example, in the context of the Frankfurt railway station measurements discussed in Section 5.6.1 [57, 58], it was concluded that only error rate (CRC) driven selection diversity could deliver a satisfactory performance.

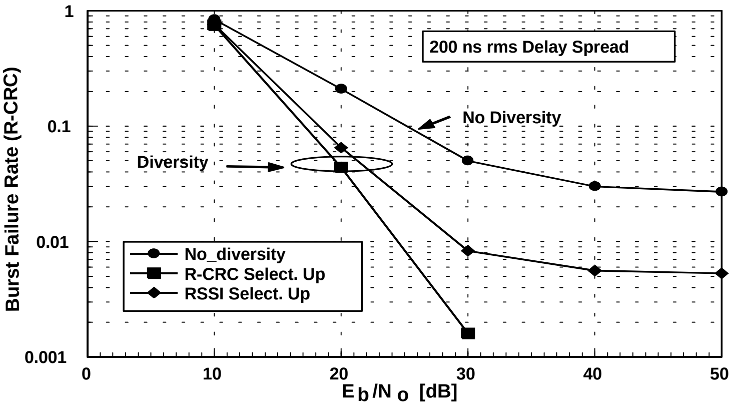


Fig. 5.18: Burst Failure Rate for a two path Rayleigh fading channel with delay spread of 200 ns

However, the use of two receiver chains at the base station (required for selection diversity) is not very practical, so implementations tend to use a switch arrangement. This means that the up-link antenna is chosen on the basis of the quality of the previous burst (a delay of 10 ms); in addition, for both selection and switch diversity, the downlink antenna is chosen on the basis of the previous up-link (a delay of 5 ms). In realistic channel conditions, it is quite possible that the channel characteristics will have changed enough during such delays for the antenna selection to be incorrect. In the extreme, the choice of antenna would not be correlated to real channel conditions, and all diversity gain will be lost [41,62].

This important limitation is illustrated in Fig. 5.19 [41], which shows that virtually all diversity gain is lost at portable speeds of 1 m/s and above when a switch configuration is used. Up-link selection diversity provides a gain of about 10 dB, independent of speed, while the downlink still degrades considerably less than in switch mode (since both diversity branches are sensed simultaneously in the uplink, providing additional information). In summary, diversity is a very powerful means to improve DECT performance under a wide range of impairments but its effectiveness can be seriously reduced under mildly dynamic conditions if the more efficient switch configuration is employed (see also chapter 3 for a more general discussion of diversity techniques).

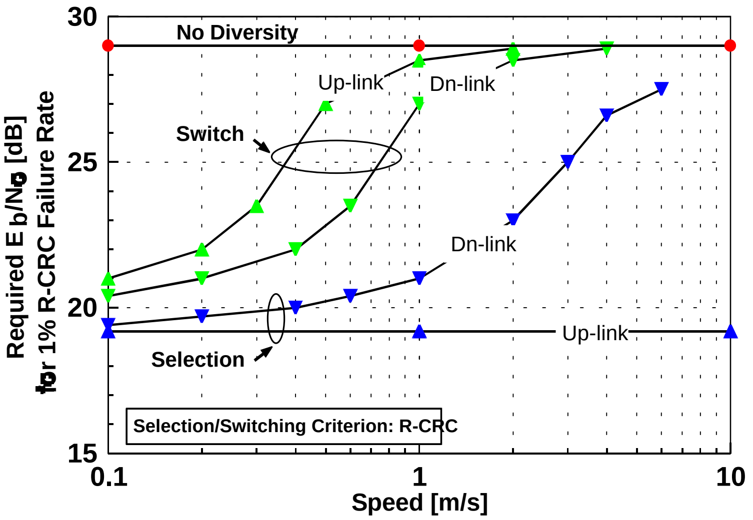


Fig. 5.19: Performance of different diversity arrangements on up-link and downlink directions as a function of portable speed

5.8.2 Diversity Techniques in Dynamic Channels

Various algorithms to reduce speed dependence and generally improve diversity performance have been proposed during the course of the project.

Combined RSSI and CRC criterion for switch diversity **[43].** In this algorithm, the up-link RSSI is averaged using a sliding window. Then an antenna switch is performed if either there is a CRC failure (as before) or the RSSI falls below a threshold (e.g. 10 dB below the current average). Both the threshold and the width of the window can be adjusted for best performance. This scheme effectively provides *soft* information in addition to the hard CRC check, which may prevent the occurrence of some CRC failures. Under Rayleigh flat fading conditions and at 1 m/s, the scheme gains about 2 dB with respect to a CRC controlled switch, but still falls well short of selection diversity (see Fig. 5.19).

RSSI prediction for downlink antenna selection **[44].** This algorithm is primarily connected with selection diversity schemes and aims at improving the performance of the downlink (which still suffers from a 5 ms delay). If both antennas have an identical CRC check result (either correct or failed), then a decision on which antenna to use is made by predicting the RSSI level at the instant of the downlink, and choosing that which gives the highest value. This algorithm gives a relatively small improvement to the downlink performance, but this is obtained at virtually no cost in complexity since all metrics used are already computed anyway, and the prediction method can be very simple.

Emulation of RSSI selection diversity [45,78]. This scheme attempts to emulate ideal selection diversity whilst using one antenna only. Considering the DECT burst structure shown in Fig. 5.13, it can be seen that overall, the preamble and packet synchronisation word carry a total of 32 bits which makes clock and frame synchronisation possible for simple receivers on a burst-by-burst basis. However, more sophisticated receivers may only require a portion of this 32 bit field to achieve synchronisation, and in particular a scheme was proposed by Kadel [77] which achieves this goal.

In this case, a significant portion of the initial preamble (typically 14 bits) becomes redundant and may be used for other purposes, such as pre-detection RSSI measurements.

The principle of operation of this scheme is shown in Fig. 5.20

Fig. 5.20. As can be seen, the receiver makes fast RSSI measurements on the two antennas, finally settling on the highest RSSI antenna for reception of the burst. As such, it will emulate ideal RSSI selection diversity in the up-link whilst operating only a single receiver. It will also improve the downlink performance since it provides knowledge of the current RSSI of both antennas.

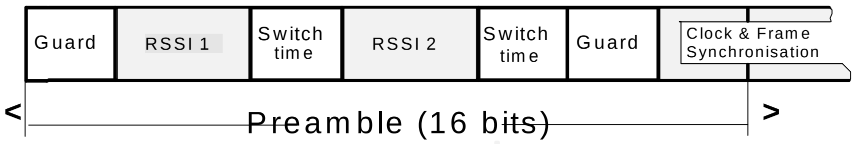


Fig. 5.20: Timing diagram for RSSI measurements on two antennas during the preamble

Practical questions of importance with this scheme are to what extent switching intervals are sufficient for switching and settling of the receiver, and the required interval for RSSI measurement. Typically, only 3-4 bit periods may be available for each antenna; however the signal is periodic during the preamble and so is the envelope. Hence signal level averaging should settle reasonably quickly. In addition, the absolute accuracy of the measurements is relatively unimportant, since only a comparative measure of the antennas is required. This scheme shows good promise for base station diversity, as well as possibly for portable diversity, since it requires one receiver only. It must operate in conjunction with a synchronisation algorithm similar to that used for equaliser initialisation, and for this reason studies of its performance when combined with equalisation have been carried out, and are discussed later.

Optimum diversity combining [46,70]. Finally, optimum diversity combining has also been evaluated for DECT. In this scheme, it has been assumed that 31 bit Gold sequences are added to each DECT burst (providing in principle different mobiles with different sequences so as to identify co-channel interferers). This is then used on reception to estimate optimum combining weights for an antenna array. It is shown that, in the up-link direction, it is possible for the base station receiver to differentiate between the wanted signal and co-channel interferers, as well as to reduce the sensitivity to delay spread.

It will be difficult to realise such gains in practice since, for example, the antenna phases would need to change during the burst to track carrier frequency offsets and in addition actual DECT synchronisation words are identical for all portables. The downlink case is more problematic as the combining weights for transmission will be incorrect due to channel variations (and the interfering environment is not identical in the up-link and downlink directions).

Antenna pattern diversity **[53].** All the above schemes use standard antenna spatial diversity. In [53], the diversity branches correspond to different patterns resulting from combining with different relative phases. This concept can provide orthogonal patterns with strong and wide nulls, and the resulting spatial filtering may provide less dispersion than omnidirectional space diversity.

5.8.3 Equalisation Techniques for DECT

In future PCS applications of DECT, both time dispersion and portable movement may be significant and simple switch diversity will not provide sufficient quality. Even the advanced diversity algorithms discussed above have limitations since they are either based on RSSI measurements or only deliver up-link gain (or both). Equalisation can therefore be considered as a possibility.

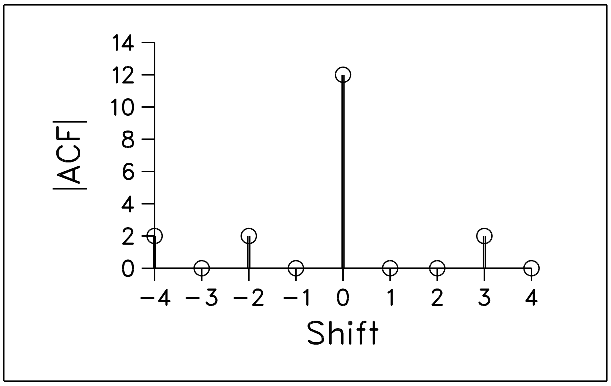
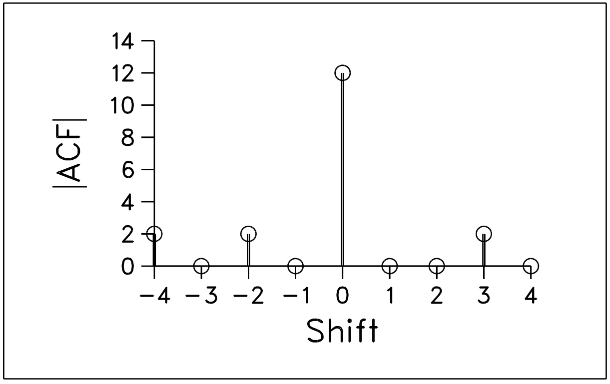


Fig. 5.21: Magnitude of the autocorrelation of the S-field subsequence starting at bit 17 with length 11 [77]

Since the design did not envisage the use of equalisation, no training sequence was provided in the DECT burst for channel estimation and synchronisation. However, there is a sub-sequence of the S-field with very useful autocorrelation properties [77], as shown in Fig. 5.21. This sequence starts at bit 17 of the S-field and has a length of 11 bits (a total of 12 modulated samples). As can be seen from the figure, this sequence would allow channel estimation for a short length channel, or even for longer lengths with relatively small error.



This sequence was used in [77] to estimate the channel, modelled by only two taps, and hence set up the table for a simple 2-state Viterbi equaliser. It was shown by simulations that such an equaliser can extend the delay spread range (in very high SNR) to at least 600 ns. Additionally, using the measurements from the Frankfurt railway station [57,58], it was found that the equaliser could deliver reasonable performance in areas where previously error driven diversity would have been required. Further, the combination of such diversity with an equaliser was found to remove completely the high SNR error floor.

A study using a Decision Feedback Equaliser was also carried out [71]. Both these structures, however, suffer from a residual lack of compatibility with the standard, since DECT units have high degree of tolerance in respect of operating carrier frequency and frequency deviation. Both equaliser structures mentioned will not operate in conditions where the relative frequency offset between the two ends of the link is greater than about 0.2-0.3% of the bit rate (about 300 Hz) [77].

A non-coherent equaliser receiver has been proposed as a means to overcome these drawbacks [72,73,74]. A basic proposal for this simply consists of a differential operation (multiplying the signal by its delayed complex conjugate) followed by a Viterbi equaliser.

It is found that the samples of the output can still be expressed as a linear combination of the original data bits plus some non-linear terms, enabling the operation of a MLSE algorithm. Further modifications to this structure have been introduced in order to extend the dispersion range and increased tolerance to frequency offset [74,78]. Fig. 5.22 shows the performance that can be obtained, with a maximum delay spread of over 400 ns at an Eb/No of 30 dB. In addition, it can support offsets close to 10% of the bit rate, which should be adequate in the DECT context.

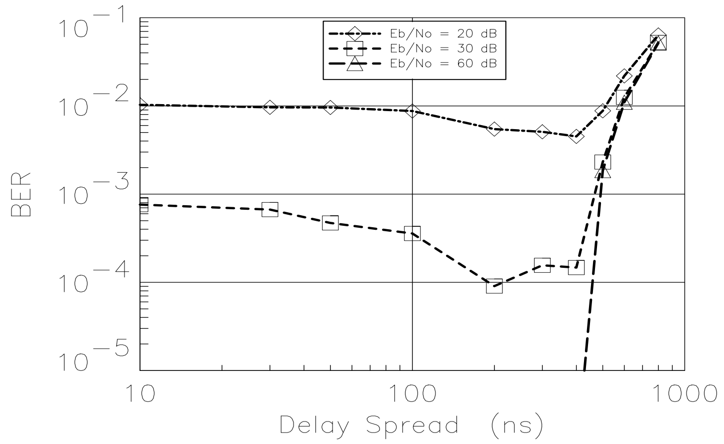


Fig. 5.22: Delay spread performance of the non-coherent equaliser [74]

5.8.4 An Advanced DECT Receiver Concept

This structure is the natural development of some of the ideas discussed in the previous sections. Since the algorithm for emulation of RSSI diversity requires only some of the S-field, and does not overlap with the equaliser training sequence, it becomes possible to combine diversity emulation and equalisation in a single receiver. Such a structure provides excellent all round performance, as found in the various evaluations carried out [78,79,80]. It can be applied to base stations as well as portables since it requires a single receiver chain (but a double antenna arrangement must be provided, as well as additional signal processing).

Table 5.11 shows an overall comparison of some of the most important receiver types discussed in this section, taking the basic (standard) receiver as a reference. Shaded boxes highlight aspects that do not quite meet performance or complexity requirements. The Table confirms that the advanced concept briefly described above (last row of the Table) provides a very robust overall performance. In fact, it has been shown by practical measurements to outperform CRC driven selection diversity, even though this makes use of two parallel receiver chains [79].

Receiver Structure	**Diversity Gain**	**Dispersion Limit**	**Speed Dependency**	**Complexity**	
				Implementation	**Signal Proc.**
Standard Receiver (LD or DD)	0 dB	80-100 ns	LOW	Single RX	LOW
RSSI-driven Diversity (Switch)	» 10 dB	170-200 ns	HIGH	Single RX	LOW
CRC-driven Diversity (Switch)	» 10 dB	350-400 ns	HIGH	Single RX	LOW
CRC-driven Diversity (Selection)	» 10 dB	350-400 ns	LOW	Double RX	LOW
Emulated RSSI-driven Diversity (Preamble-based)	» 10 dB	150-200 ns	LOW	Single RX	LOW
Non-coherent Equaliser	» 0 dB	450-530 ns	LOW	Single RX	HIGH
Preamble-based Diversity & Non-coherent Equaliser	» 10 dB	480-560 ns	LOW	Single RX	HIGH

Table 5.11: Comparative performance of DECT receivers

5.9 A DECT Field Trial in a Multipath Environment

Magne Pettersen, Rune Harald Rækken, Bjørn Erik Eskedal (Telenor R&D, Norway),
Joar Løvsletten, Jan Tore Deilkås (Telenor Mobile AS, Norway)

This section describes briefly some performance studies using a DECT field trial network set up by Telenor of Norway in order to gain experience and evaluate the subscribers' interest in mobility at the local level [75,76]. Other such trials have been reported (e.g. [54]), but this is used here as an illustrative example. Førde, the location of the trial, has 9000 inhabitants and is located in a mountainous area creating challenging radio propagation scenarios. The main reason for choosing Førde for the field trial was that the distances between residential and business/industrial areas are relatively short. If roaming is allowed between different environments, coverage can be provided within the entire local community.

The DECT trial system at Førde was delivered by Ericsson, and consists of 240 handsets (portable parts - PP), 160 radio base stations (RBS) and a central control fixed part. In all, the system can carry 40 simultaneous calls. Environment characteristics and system planning aspects of the field trial are shown in Table 5.12.

Space diversity is employed on the RBSs: a simple switching diversity algorithm based on the cyclic redundancy check (CRC) of the previous frame is used to switch between antennas. Average distance between RBSs equipped with omnidirectional antennas and customers residences is approximately 50 meters. When the base stations are equipped with directional antennas the average distance to the customers is increased to 80-90 meters. The maximum cell radius in the system is 400 meters.

Services offered. Approximately 50 households and 55 business/industry companies participate in the trial. The number of handsets used in a family varies typically between 1 and 3. By allowing in some cases several family members to have their own handset with a dedicated telephone number, a personal service is offered to the customers. The number of handsets offered to a company varies between 1 and 11. Calls can be made and received within the entire covered area (2.0-2.5 sq. km) and seamless handover is performed between all 160 base stations. Some trial customers both live and work within the coverage area, benefiting from the possibility to use the same handset both at work and at home. During the test period private customers pay the same tariff as for fixed telephone. The same offer is given to business users. In addition, all normal PBX functions are provided allowing business users for instance to make free internal calls within the covered area.

Experiences from the trial. Most existing DECT products have been designed and targeted for indoor applications. However keeping in mind the potential of DECT in an outdoor environment both as a technology providing local mobility and as a fixed radio access solution (replacing copper), one of the main technical goals was to understand the strengths /weaknesses and improvements needed on current versions of the DECT system in order to operate in both indoor and outdoor environments.

	Residential area	**Downtown area**	**Business/ Ind. area**	**Recreation area**
Area characteristics	0.9 km^2 700 residences both hilly and flat areas with some vegetation	0.4 km^2 shops, public buildings (3-6 floors) flat area	0.4 km^2 massive buildings with thick concrete walls flat area	0.5 km^2 fields, open green areas, sporting areas
Planned coverage	outdoor indoor in most rooms except basements	outdoor indoor in public areas and for all business customers partly in shops	outdoor indoor in areas of importance for the trial customers	outdoor indoor in public areas
Installed base stations	64, all outdoor	15 outdoor 40 indoor	11 outdoor 19 indoor	3 outdoor 6 indoor
Subscribers	52 families	27 business customers	16 business customers	4 business customers
Number of handsets	90 handsets	74 handsets	58 handsets	10 handsets

Table 5.12: Environment characteristics and system planning aspects of the DECT field trial at Førde [76]

Regarding indoor coverage, several aspects were found that can minimise the number of base stations whilst still achieving high speech quality. These include accurate positioning of the base stations, 3-dimensional planning strategy, knowledge of the interior constructions and types of reflecting objects and materials of ceiling, walls and floors attenuating the signal strength. Experience from the trial has given valuable information about the expected cell range in a variety of different indoor environments ranging from more than 50 metres in open hall areas to less than 15 metres in heavily reinforced areas. As a result of the limited cell radius careful site planning can reduce the number of indoor base stations by more than 30 %.

In outdoor areas, many subjective tests have been performed giving valuable information on the system performance. On the positive side, it has been found that the speech quality is in general good (e.g. better than GSM) as long as there exists a free line of sight path between the base station and the terminal, and no major reflecting objects are in close vicinity. Good speech quality has been obtained more than 400 m from the closest BS (without directive antennas) and approximately 1 km from base stations using directive antennas. Finally, tests show that it is possible to communicate and perform handovers whilst driving even though the system was not developed for use in cars. However a certain degradation in quality is experienced.

On the other hand, it has also been found that the link quality is highly dependent on whether line-of-sight (LOS) is available, and that the speech quality is variable in open square areas (typically surrounded by reflecting buildings) even when there exists a LOS path between the BS and the terminal and the average received signal strength is high. The link quality is also dependent on whether the user moves or stands still, and is affected by the user's orientation and positioning of the handset relative to the base station.

However, the overall impression from customer surveys indicates that most of the customers are satisfied with the DECT QoS within the planned coverage area. In the following, the focus will be on outdoor problem areas, pointing out possible solutions to aid in the system planning.

5.9.1 The Measurement Equipment

Telenor R&D’s channel sounder [59] is based on a frequency sweep technique, and has a maximum measurement bandwidth (BW) of 200 MHz. Only instantaneous impulse responses (IRs) are treated; based on these, the cumulative distributions of the Delay Spread and the Delay Window are obtained [59] (see chapter 2 for definitions of these).

The channel sounder can be used to derive parameters indicating performance of DECT in a multipath environment. The delay spread gives an indication of radio system performance for a standard DECT receiver, while the delay window is well suited to indicate the performance of a receiver that employs a channel equaliser. Simultaneously, the Symbionics DECT Propagation Tester provides measurements of a number of parameters, including signal level (RSSI) and BER. Handsets are included to allow subjective evaluation of speech quality.

Microcellular city street and city square measurements have been performed in the Oslo area, as reported in [59]. In city streets delay spread values are usually small, and multipath propagation does not limit DECT performance. In city squares with larger dimensions, multipath propagation would often cause severe problems to DECT communications, raising the need for some means to combat the influence of frequency selective fading. To verify DECT vulnerability to multipath propagation, laboratory measurements were performed with a fading simulator between the TX and the RX of the Symbionics DECT propagation tester. The BER shows a strong dependence on delay spread, and the DECT performance limit of BER 10^{-3} [77] is reached at delay spread values of about 100 ns.

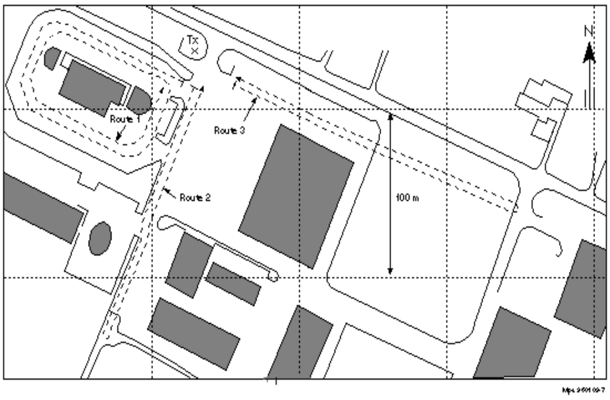


Fig. 5.23: Førde, measurement routes 1-3. Shaded areas represent buildings

5.9.2 Førde Measurements

Measurement scenarios. Measurements were performed at different locations within the coverage area of the DECT trial system, particularly in regions where QoS was reported to be unsatisfactory despite sufficient signal level [75]. In all measurements, the RX antenna was omnidirectional with 2.1 dBi gain positioned on a 2 m high pole fastened to the car. All measurements were made at a speed of about 20 km/h (approximately 30 cm between IRs). Fig. 5.23 shows routes 1 to 3.

In routes 1, 2 and 3 the TX antenna was omnidirectional, elevated to 3.5 meters, and positioned as shown in the figure. Outside the map, to the south, there is a steep hill rising about 300 meters above the measurement area. Along route 3 the direct path was sometimes blocked by moving cars. Most of the buildings in this area were brick or stone houses of two or three floors. In route 4, an omnidirectional TX antenna elevated to 5 meters was used. There was a metal shed between the TX and RX antennas, blocking the direct path in most of the route.

Measurement routes 5 and 6 are shown in Fig. 5.24. In both routes, the TX antennas were directional pointing south, parallel to the road. TX antenna heights were 4 meters. In route 5 the TX antenna gain was 7.1 dBi, and 14.1 dBi in route 6. There was a line-of-sight path from the TX to the road of route 6, but the LOS was sometimes blocked by residential wooden houses.

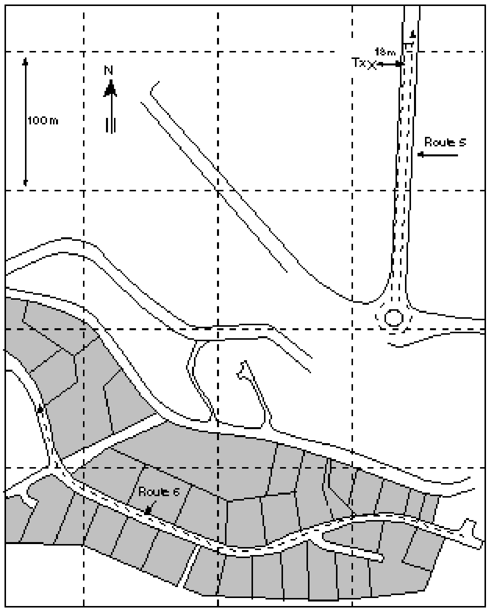


Fig. 5.24: Førde, measurement routes 5-6. Shaded areas represent lots with residential houses

***Measurement results* [75].** The delay spread and window parameters were measured using the channel sounder, and their cumulative distributions were calculated. In addition, the DECT propagation tester was used to measure BER and RSSI. and the 50 and 90 percentiles of the delay spread and 90% delay window parameters are shown in Table 5.13.

From the DS measurements, only route 3 would be expected to have propagation conditions that the basic DECT receiver could handle [77]. The others have many locations with delay spreads exceeding 10% of the DECT bit interval. In route 4 the DS is almost all the time above 100 ns, indicating that DECT communication without diversity or channel equalisation would be impossible. Both routes 4 and 6 have delay spread values which exceed those reported to be possible to handle by using diversity techniques. It should be kept in mind, however, that the routes are chosen from areas where QoS problems have been reported. Some of the time dispersion could easily have been removed with different RBS location. In routes 3 and 6 the maximum distance between RX and TX exceeds the normal cell radius used in the Førde system.

Route	**Delay Spread (ns)**		**Delay Window (ns)**	
	50%	90%	50%	90%
1	76.6	218.9	40	440
2	75.3	141.1	60	260
3	41.1	96.7	40	60
4	272.0	316.9	640	700
5	60.5	132.7	40	120
6	106.6	415.1	100	1040

Table 5.13: Measurements from Førde

The time dispersion is severe on both routes 5 and 6, showing that the use of directive antennas to extend the coverage area of the RBS may cause problems due to time dispersion when the receiver is not located within the main lobe of the TX antenna pattern. This is because strong reflections from the most strongly illuminated areas can reach the receiver with considerable excess delay due to the larger dimensions of the cell. It is also noted that, in general, the delay spread has its largest values in positions where there is no LOS path from the transmitter to the receiver.

Error! Not a valid link.

Fig. 5.25: BER versus delay spread from Førde

It was expected that the high delay spreads found among these measurement routes cause high BER values. To verify this, averages of the delay spread taken over the same distance as the BER were calculated. Fig. 5.25 shows BER as a function of delay spread for all the measurements made at Førde. The RX level was rarely below -70 dBm, and the points for which the RX level was below this level have been removed (so as to focus on the effect of time dispersion). The plot also shows the regression line, which crosses the BER of 10^{-3} at approximately 120 ns.

5.9.3 Conclusions from Field Trial and Measurements

The experience in the trial shows that the DECT technology is a strong candidate for providing speech services and mobility in indoor domestic/business/industrial environments. However, for providing outdoor local mobility the technology is relatively immature and too sensitive to radio propagation conditions [75,76].

For this reason, wideband multipath measurements at 1950 MHz and DECT performance tests have been performed in a number of environments in the DECT field trial area where unacceptable QoS was reported. There was severe time dispersion in many of the routes, and in some of the cases the delay spread exceeded values reported to be handled by DECT employing simple diversity schemes. The use of directive antennas can extend the range of the cell, but the multipath situation can worsen if the receiver is not located within the main lobe of the TX antenna radiation pattern. The dispersion also increases considerably if the LOS path is obstructed.

Some of the time dispersion affecting DECT QoS could easily have been reduced by a different choice of RBS location, demonstrating the importance of proper base station planning. DECT performance would in any case improve significantly if advanced diversity techniques or a channel equaliser are introduced to cope with multipath propagation [78,79]. This should be born in mind when planning outdoor DECT implementations for public use.

With an improved air interface, the high capacity of DECT, the variety of services supported by the standard and its simple/flexible network structure makes it a very interesting candidate both as a pure copper replacement connecting subscribers to the fixed network and as a public radio access solution providing local mobility.

5.10 Traffic Capacity for the DECT system

Valerio Palestini (CSELT, Italy)

This section deals with DECT capacity for service provision. DECT enables both voice and data services at bit rates suitable, for example, for ISDN connection, high capacity and a dynamic channel selection mechanism which avoids the need for frequency planning. DECT is in fact an access system to networks such as PSTN, ISDN, GSM, etc.

One DECT transceiver [83] can manage up to 12 bi-directional voice channels, due to the frame architecture shown in Fig. 5.26. A bi-directional voice conversation uses a so-called "duplex bearer", comprising two time-slots separated by 5 ms on the same carrier.

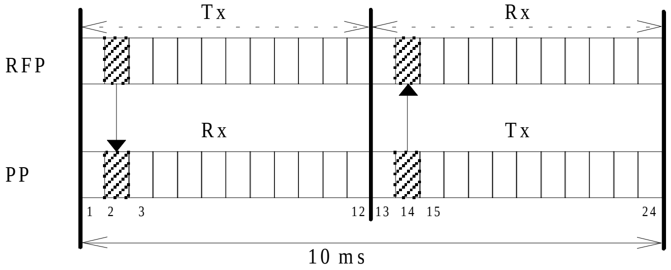


Fig. 5.26: Frame architecture for one DECT duplex bearer

Capacity results are provided for two of the most commonly mentioned applications of DECT - the WPBX (Wireless Private Branch eXchange) and RLL (Radio Local Loop). DECT was in fact originally designed with WPBXs in mind, but many other possibilities proved to be very interesting, and particularly the replacement of the last part of copper wires connecting a subscriber to the fixed network by a radio path (usually referred to as RLL). In both cases, the capacity results are obtained by simulations, using the ad-hoc scenarios described.

5.10.1 WPBX application

Voice service. Terminals are randomly positioned (with uniform distribution) within a reference three-storey building 100 metres x 100 metres x 9 metres, in which 16 base stations are regularly spaced in each storey (Fig. 5.27). Terminals are considered to be static during the call; each terminal generates 0.2 Erlang of traffic and the mean duration of a call is 120 seconds. The radio propagation model assumes a propagation decay equal to 3.5, an attenuation between floors of 15 dB, an additional factor in the range +/- 10 dB to account for shadow fading, and a Rayleigh fade margin of 10 dB, if antenna diversity is applied, or 20 dB, without antenna diversity.

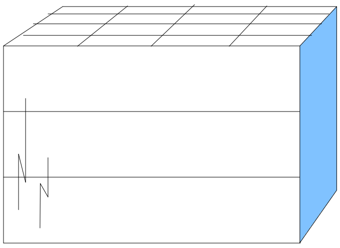


Fig. 5.27: Reference building

The system spectrum allocation, the radio parameters (transmitted power, receiver noise floor, adjacent channel rejection factors, etc.), and the call procedures (set-up and handover for both single and multi-bearer channel allocation models), are in accordance with the DECT specifications [83]. The aim of this work is to evaluate, for each type of terminal, the grade of service (GOS) versus the number of bases per floor:

$$\mathrm{GOS} = \frac{\text{Number of blocked calls} + 10 \cdot \text{Number of interrupted calls}}{\text{Number of total calls}} \qquad (5.3)$$

In works dealing with DECT simulation performance [84], the maximum acceptable GOS is 1%. Different scenarios are taken into account:

- a single system in the building;
- three different systems (one per floor) synchronised or unsynchronised.

As a first assumption, systems are considered unsynchronised if frames are not aligned; in addition, the shift between the first timeslot of the frames of each system is taken to be not greater than one timeslot as shown in Fig. 5.28.

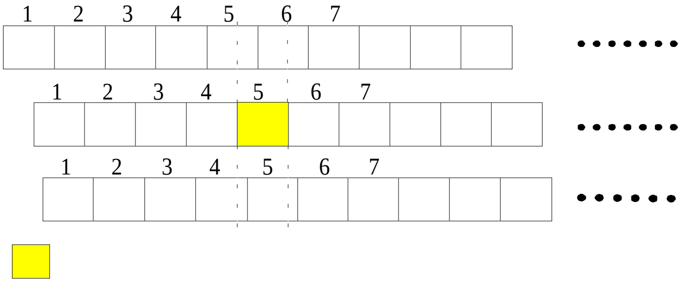


Fig. 5.28: Three unsynchronised systems in the building

When a single WPBX system is introduced in the building with a floor attenuation of 15 dB, the maximum capacity of the system in terms of Erlang per RFP reached with a GOS equal to 1% is about 5.6 Erlang, corresponding to 9000 Erlang/km^2/floor; if a higher separation between floors is introduced (i.e. Af=20 dB), this value becomes 6 Erlang (9600 Erlang/km^2/floor).

In the second scenario, a different WPBX system is positioned on each floor of the building; terminals can only set up a call and make handovers with base stations of their system, that is of their floor. The cases of all systems synchronised and all unsynchronised are taken into account. The comparison between the three scenarios is shown in Fig. 5.29.

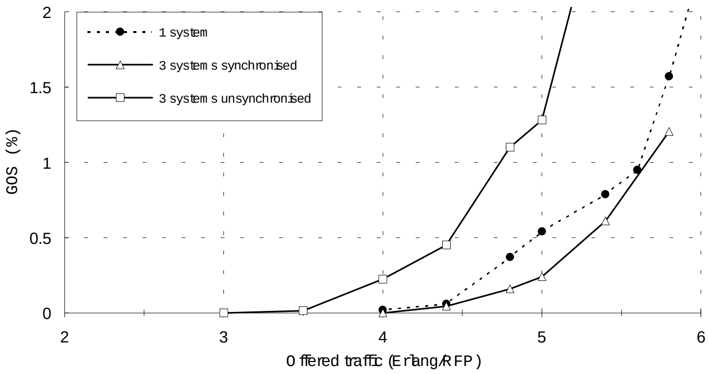


Fig. 5.29: Offered traffic per RFP with three systems in the building (synchronised and unsynchronised)

The results obtained by simulations show that coexistence of different WPBX systems, also unsynchronised, is possible with a loss in capacity, in the worst case, of less than 20%; in fact the total capacity obtained is about 7400 Erlang/km^2/floor, instead of about 9000 Erlang/km^2/floor for the reference case of 1 system in the building with Af=15 dB.

	Af (dB)	**Erlang/RFP**	**Erlang/km^2/floor**
1 system	15	5.6	9000
	20	6	9600
3 systems synchronised	15	5.7	9100
3 systems unsynchronised	15	4.6	7400
	20	5.8	9300

Table 5.14: Traffic capacity for different system scenarios.

Better performance is obtained when the physical separation between different systems is higher, that is when the floor attenuation considered is 20 dB. In fact, in that case, the loss in capacity when 1 system in the building is substituted by 3 unsynchronised systems is almost negligible: the total capacity decreases from 9600 Erlang/km^2/floor to 9300 Erlang/km^2/floor. Results are summarised in Table 5.14.

Mixed voice-data scenario. The results reported hereafter on the performance of DECT in a mixed voice-data scenario have been obtained under conditions similar to the case of voice service only; the differences are in the dimensions of the reference building, (now 60 m x 60 m x 9 m) and the traffic per terminal (0.15 Erlang instead of 0.2 Erlang).

Terminals are considered to be static during a call, so that only intra-cell handover can occur. The total number of terminals (belonging to the same DECT system) in the building is 540 (so that, on average, there is one per 20 square metres of floor). The results are presented in the cases of either 100% voice terminals or 80% (i.e. 432) voice terminals, 10% (i.e. 54) ISDN terminals and 10% fax terminals. It is assumed that a voice terminal requires one duplex channel, an ISDN terminal requires one normal duplex channel for signalling plus one or more duplex channels (multi-bearer symmetric connection), and a fax terminal requires one normal duplex channel for signalling plus one or more double simplex channels (multi-bearer asymmetric connection). In the two latter cases, a multi-bearer connection is defined by the minimum number of bearers (Bm) that the connection can accept and the target number of bearers (Bt) needed by the connection. These bearers, in general, could be obtained from different base stations, but here it is assumed that they are obtained from the same base.

The mean traffic at the base is calculated as the average number of slots used at the base. For each type of terminal the average number of active connections per base is also computed. As in the case of voice service the reference value of GOS is set to 1%.

The performance results, presented in Fig. 5.30 and Fig. 5.31, show five curves in each graph; one for the reference case of 100% voice terminals and four for the case of 80% voice, 10% ISDN and 10% fax terminals, distinguishing, for the latter case of an asymmetric connection, between the up-link (terminal-to-base station) and the down-link (base station-to-terminal).

In all cases it can be seen that for fax terminals the up-link is more critical than the down-link, as base stations are affected by interference from other base stations transmitting in the same time slot (particularly those vertically aligned on different floors); the same happens in the down-link for voice or data terminals, but as they are randomly positioned this effect is less significant. A possible action to improve performance can be to install base stations in such a way as not to be aligned on adjacent floors.

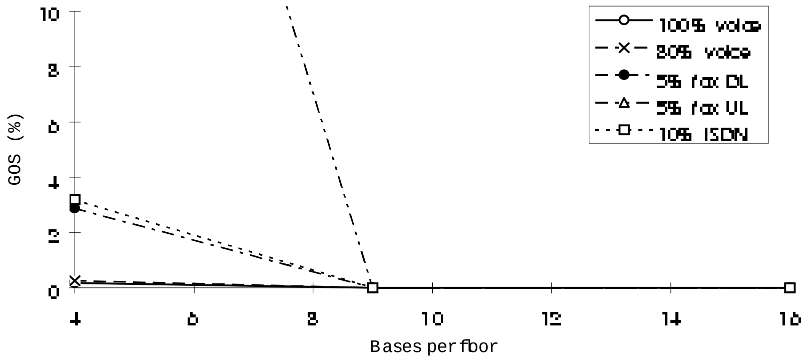


Fig. 5.30: Performance with diversity in a mixed voice-data scenario. The minimum (B_m) and target (B_t) numbers of bearers are as follows:

$B_m=B_t=3$, for ISDN terminals

$B_m=2$, $B_t=3$, for fax terminals

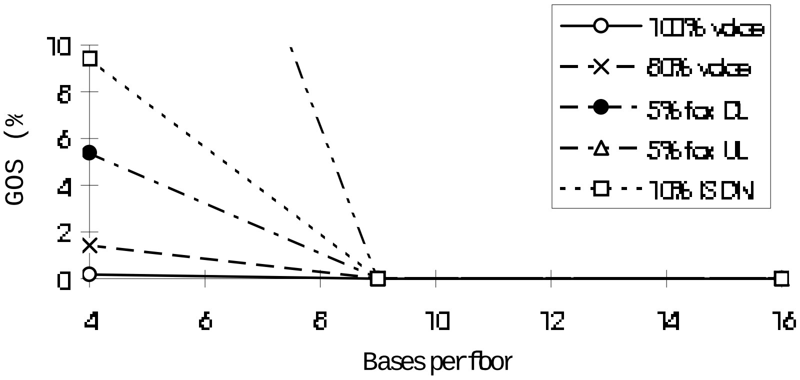


Fig. 5.31: Performance with diversity in a mixed voice-data scenario. The minimum (B_m) and target (B_t) numbers of bearers are as follows:

B_m=2, B_t=4, for ISDN terminals

B_m=B_t=2, for fax terminals

		Number of connections per base				Mean traffic per base	
Bases per floor	**Diversity**	**Voice**	**ISDN**	**fax uplink**	**fax downlink**	**Mixed voice-data**	**voice only**
4	with	5.44	0.23	0.1062	0.12	6.7	6.9
9	with	2.42	0.10	0.06	0.05	3.0	3.1

Table 5.15: Traffic evaluation in a mixed voice-data scenario. For fax terminals the minimum (B_m) and target (B_t) number of bearers are B_m= 2, B_t= 3; for ISDN terminals B_m= B_t=3. This table shows the average number of connections per base for each type of terminal and the mean traffic per base in terms of average number of used slots.

The voice service does not seem to be much impaired in the mixed voice-data scenario with respect to the case of voice only; in the case of 9 bases/floor and diversity, for all the examined kinds of terminals the GOS is below 1%.

Table 5.15 and Table 5.16 show the mean traffic for each kind of terminal, in terms of average number of active connections/base, and the total mean traffic, in terms of average number of slots/base. It is worth noting that for voice only and 4 bases/floor with diversity (a case in which the GOS is less than 1%) the traffic is 6.9 Erlang/base, which corresponds to about 7700 Erlang/km^2/floor. For mixed voice-data services, the necessary number of bases/floor to have GOS less than 1% is 9 (if diversity is applied), for all kinds of terminals; the tables indicate that in all the examined cases the mean traffic is in the range 3-3.3 Erlang/base, corresponding to 7500-8200 Erlang/km^2/floor.

		Number of connections per base				**Mean traffic per base**	
Bases per floor	**Diversity**	**Voice**	**ISDN**	**fax uplink**	**fax downlink**	**Mixed voice-data**	**voice only**
4	with	5.37	0.18	0.15	0.17	6.7	6.9
9	with	2.61	0.08	0.09	0.08	3.3	3.1

Table 5.16: Traffic evaluation in a mixed voice-data scenario. For ISDN terminals the minimum (B_m) and target (B_t) number of bearers are B_m=2, B_t=4; for fax terminals B_m=B_t=2. This table shows the average number of connections per base for each type of terminal and the mean traffic per base in terms of average number of used slots

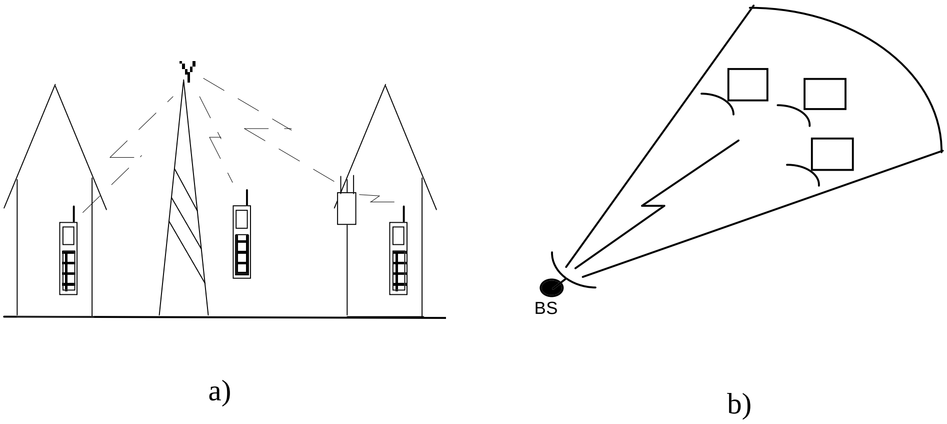
Conclusions. Computer simulations of the DECT wireless PBX application have shown that in the case of voice service only, with one DECT system in the reference building, the capacity is around 9000 Erlang/km^2/floor. This value is not impaired if three different systems (one per floor) coexist in the same building, provided that they are synchronised; if this is not the case, a capacity loss of under 20% may be expected. If DECT terminals are present that require multi-bearer connections (e.g. ISDN and fax terminals), traffic densities of the same order may still be achieved at the same GOS, but at the expense of roughly doubling the number of base stations per reference area unit.

5.10.2 RLL Application

This section focuses on the possibility of replacing the last part of copper wires connecting a subscriber to the fixed network by a radio path; this application is usually referred to as the Radio Local Loop (RLL). The interest in RLL applications is growing with the opening of new markets in Eastern Europe and in other developing countries.

Many existing and proprietary standards have been analysed [86], but, as yet, none has emerged as the clear favourite for this type of application (all systems considered show pros and cons depending on factors such as the environment that is assumed).

Two possible scenarios are shown in Fig. 5.32; in a), a base station that allows local mobility to the user, both inside and outside buildings, with the support of repeater units, and in b) the case of the provision of the basic telephony to a few isolated houses is considered (in this case it is also possible to extend the range of the base station by means of a repeater).



a) b)

Fig. 5.32: Some typical scenarios for the RLL application

DECT is one of the standards being considered; in fact, a profile for this kind of application is being standardised [87] in the sub-technical committee ETSI RES3.

Impact of the Wireless Relay Station on the System Capacity. A scenario in which the service allows local mobility to the user, both inside and outside buildings, implies facing the propagation problems due to additional wall attenuation. To offer a suitable indoor coverage, the relay function seems to be a viable solution. For this purpose, an additional unit, here called Wireless Relay Station (WRS), is needed.

Two different architectures have been proposed during ETSI meetings and an Interim ETS [81] including both proposals has been written. The main difference between the two solutions, called respectively CRFP and REP, is the occurrence of the retransmission of the slot at the WRS.

The CRFP may receive and transmit, during any slot of a frame a duplex bearer to either the PP and the RFP, supported by a combination of a CRFP Rx and Tx slot separated by one half frame (a typical frame multiplexing structure is shown in Fig. 5.33).

The REP unit receives a slot in one frame and retransmits it in the same frame (Fig. 5.34); in addition the REP, in order to maintain the symmetry of the bearers, sets up a new kind of bearer towards the RFP: the Double duplex bearer.

As an example, in the next section the performance of the REP unit will be evaluated by means of some computer simulations in which the system grade of service (GOS) is calculated as described above.

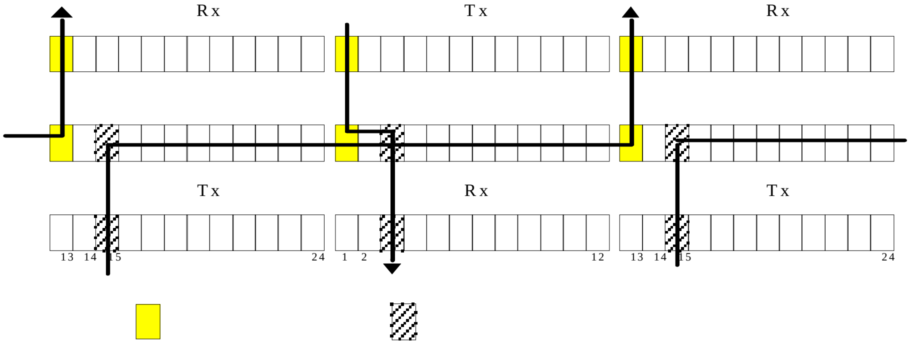


Fig. 5.33: Typical frame architecture of the CRFP unit

REP unit. The REP unit can use a simplified RFP hardware and an adapted software with some modifications in the MAC (Medium Access Control) layer. It has two antennas: one, usually directional, points to the strongest RFP that supports the REP-RFP outdoor link, and an omnidirectional one for the REP-PP (Portable Part) indoor link.

The basic working idea is to make the REP switch continuously from transmit to receive mode on a slot by slot basis (after the initial synchronisation to the strongest RFP). It duplicates and re-transmits the received burst on the other slots, within the same half frame. This previous solution proposed in [82] has been modified, because the speech service was not supported using a duplex bearer as specified.

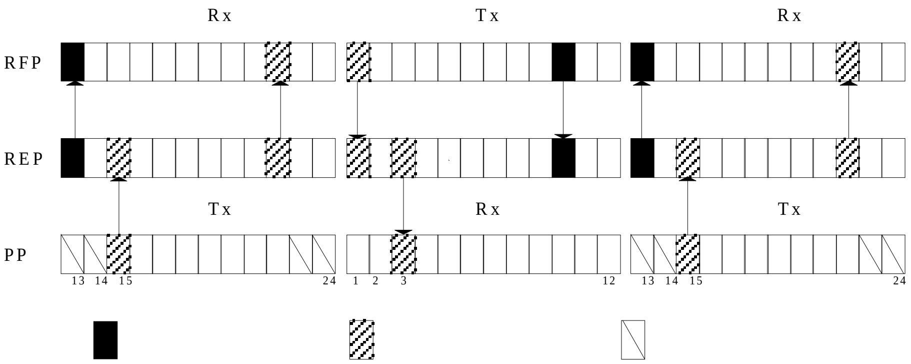


Fig. 5.34: Typical frame architecture of the REP unit

In order to consider as duplex the two channels involved in the same connection between RFP and REP, a new bearer is introduced, containing identity messages (Nt). This allows a good exploitation of DECT Dynamic Channel Selection Algorithm, as the position of the two mentioned channels does not have to be static. As shown in Fig. 5.34, after an initial set-up on the PP-REP link, the repeater chooses two other physical channels to close the connection with the RFP. This new type of bearer is called "*double duplex bearer*", and is composed of a pair of duplex bearers referring to the same connection at MAC level; the duplex bearers share their simplex bearers for the information flow [83].

The REP unit can reduce the required channel allocation by sharing the bearers between connections. As shown in Fig. 5.35, two Portable Parts use the same link from REP to RFP (Shared link) in order to maintain symmetry at the RFP for both connections. This process is called "*interlacing*".

REP performance. The REP performance is evaluated by simulation, taking into account the interlacing procedure during the set-up of the "double duplex bearers" (the two duplex slots for the REP-RFP link). Two very simple cases are taken into account, in order to estimate the capacity of the system using a REP repeater; in the first case, 1 RFP and 1 house with a REP are considered (Fig. 5.36a), whilst the second comprises 1 RFP and 2 houses with one REP each (Fig. 5.36b).

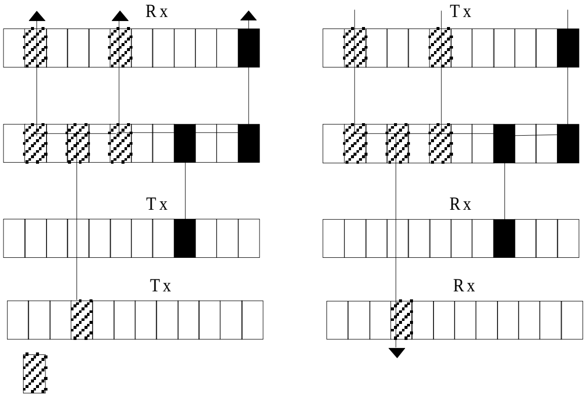


Fig. 5.35: Example of the interlacing procedure

Some tests made for RLL applications [85] have shown that communication quality rapidly decreases for distance values of more than 70 m without a WRS. In the two scenarios a distance between REP and RFP of 90 m has been chosen in order to analyse almost only connections between PP and RFP through REP.

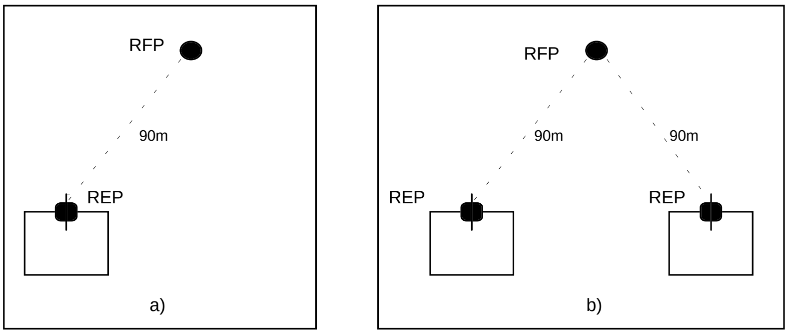


Fig. 5.36: The two simulation scenarios considered

A variable number of users with a traffic of 70 mErlang each are positioned inside the houses. The propagation law taken into account in the simulation is:

Attenuation = 53 + 20log(distance) + shadowing + wall attenuation (15 dB)

For both cases the capacity of the system is evaluated with and without the interlacing procedure described above.

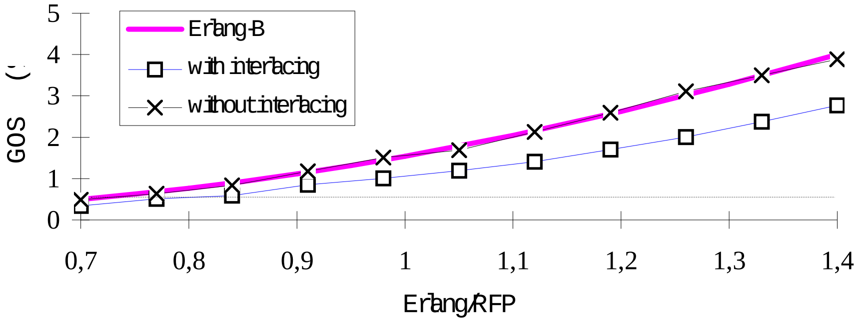


Fig. 5.37: GOS versus the Erlang/RFP in case of 1 RFP and 1 REP

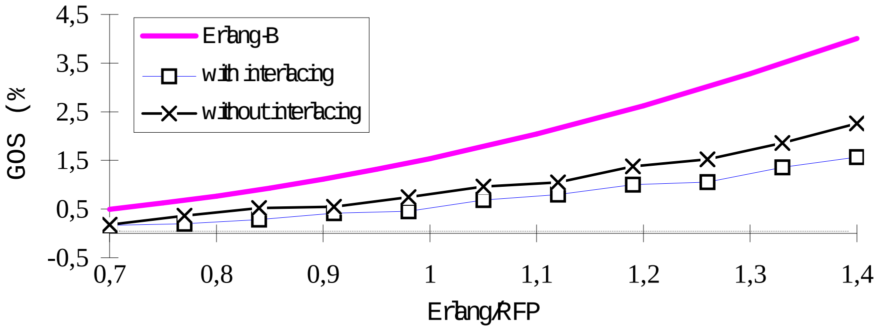


Fig. 5.38: GOS versus the Erlang/RFP in case of 1 RFP and two REPs

Both Fig. 5.37 and Fig. 5.38 show an improvement when using the interlacing procedure, since this decreases the occupation of the timeslots at the base station, allowing other direct connections or calls through the repeater.

In fact, as shown in Fig. 5.35, without the interlacing procedure the maximum number of connections to an RFP through the REP is 4, because each connection needs two links to the RFP: that means a traffic per RFP equal to 0.7 Erlang (i.e., 10 users) with a GOS of 0.5% and equal to 0.84 Erlang (12 users) with 1%. The curve is very close to the traffic at an RFP with only 4 available channels obtained with the Erlang-B formula. However, with the interlacing procedure and a GOS of 0.5%, the traffic per RFP becomes 0.84 Erlang (12 users), whilst at 1% about 1.1 Erlang (15 users) can be supported.

Interlacing also improves capacity in the second scenario, but less so than in the first. Users are now distributed between two houses, and therefore the number of connections through each REP decreases and so does the possibility of interlacing two different connections.

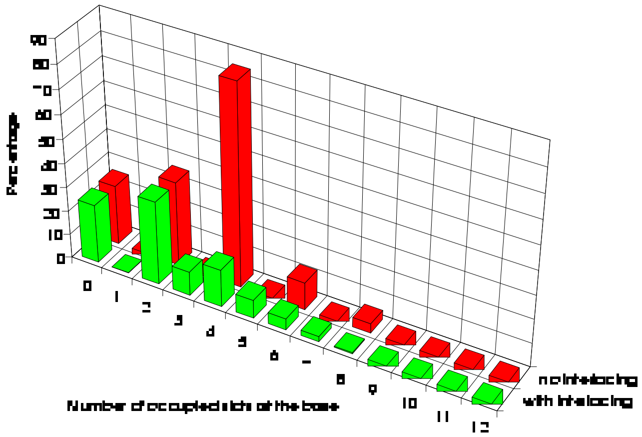


Fig. 5.39: Distribution of occupied slots at the RFP

As an example, Fig. 5.39 shows the distribution of occupied slots at the RFP, with reference to the first scenario. It can be seen that without interlacing only the even slots are used, while with interlacing the distribution is better spread over the slots, ensuring a better exploitation of the resources.

Conclusion. A Wireless Relay Station can be profitably introduced in a RLL application based on the DECT system, in order to guarantee a better quality and coverage of the area and a bigger range of the system. It does introduce a capacity limitation, since it has been verified that, using a REP, the mean traffic per RFP is less than 1E for a GOS of 0.5%.

This capacity limit seems to be acceptable in a RLL application where the user density and the mean traffic per user are both expected to be much lower then in a business environment. This means that in the case of a low density area, a WRS can be a more attractive and economic solution than an RFP.

5.11 References

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