Second Generation Fixed Broadband Wireless Access Systems: Requirements, Architecture and Performances

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ABSTRACT

The local loop market deregulation and the increased data traffic demand have been the main drivers behind the development of 1st generation Broadband Wireless Access (BWA) systems. Ericsson has developed a 1st generation BWA in the 24 to 31 GHz bands exploiting a TDM/TDMA/FDD scheme and supporting voice and data services. An efficient MAC protocol provides fast dynamic allocation of the capacity, exceeding 30 Mb/s net throughput.

Approach to 2nd generation systems has started already, with main goals of throughput enhancement and enabling of low cost equipment. Such systems will be still based on a point-to-multipoint cellular architecture providing high-quality access (BER < 10^{-11}), at net throughput exceeding 115 Mb/s in 28 MHz.

In this paper, after a short overview of 1st generation system features, requirements, architecture and performances of 2nd generation systems are described. Main results of investigations upon some key implementation aspects are also reported.

1. INTRODUCTION

New operator requirements for access systems, the advent of co-existence standards in both Europe and United States, the deregulation of the local loop market and the increased users' demands for data traffic at wide bandwidth have been driving manufacturers in developing 1st generation Broadband Wireless Access (BWA) systems.

The success story of MINI-LINK point-to-point Radio family and the ownership of novel integrated microwave technologies suitable for low cost production, based on Multi-Chip Modules (MCM), motivated ERICSSON to develop a point-to-multipoint BWA system in the applicable frequency spectrum (e.g. 24, 26, 28 and 31 GHz).

The system, known on the market as *MINI-LINK point-multipoint*, is based on a Single Carrier Time Division Multiplexing/Time Division Multiple Access/Frequency Division Duplex (TDM/TDMA/FDD) scheme, offering both voice and data services to the end user. An efficient Medium Access Control (MAC) protocol allows fast and dynamic allocation of the available air capacity, on a millisecond basis.

The net throughput over the air interface can exceed 30 Mb/s. Line of Sight (LOS) paths are required, whose length can be typically 3 to 6 Km depending on rain zone and service availability.

The modulation scheme adopted is a four levels constant envelope (C-QPSK), also known as Tamed Frequency Modulation (TFM), allowing 37.5 Mb/s in 28 MHz symmetric RF channels, while enabling very high system gain. Key system features of this product are summarized in table 1.

Frequency Bands (GHz)	*24, 26, 28, 31*
Network Topology	*point-multipoint (PmP), cellular*
Transmission Technology	*FDD/TDMA, Single Carrier*
Modulation	*C-QPSK, 37.5 Mbps in 28 MHz*
Channel Coding	*Softly decoded Block code*
Maximum TX Power	*+23 dBm*
RX Threshold (BER=10^{-6})	*-79 dBm @ 26 GHz*

Table 1: Key Features of ERICSSON 1st generation BWA.

2. SECOND GENERATION BWA SYSTEMS

The conceptual layout of a typical Broadband Wireless Access Network is depicted in figure 1.

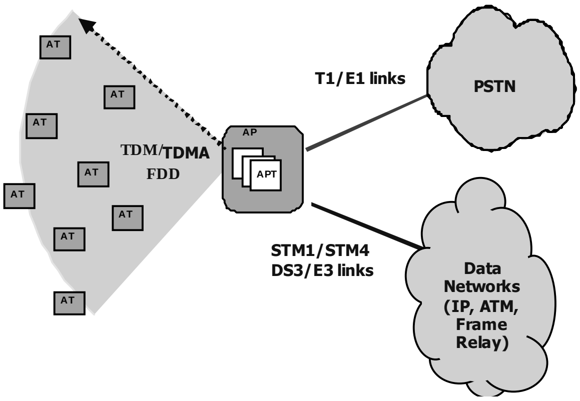

Figure 1: Typical BWA network layout.

2.1 Drivers

Main driver toward 2nd gen. BWA systems has been the desire of enhancing spectrum efficiency with no sacrifice of system coverage and interference rejection performances and without hampering Access Terminal (AT) costs. Higher throughput could be exploited either by allowing more users sharing the same frequency channel or by increasing the average throughput per AT.

Another important issue addressed has been the equipment cost, which is very important (especially for AT) in determining the success of *wireless access* technology against competitive ones (e.g., optical fibre or Digital Subscriber Line - xDSL).

All 1st generation systems are proprietary systems; no interoperability is foreseen between equipment coming from different manufacturers. On the other hand, the existence of an interoperable standard can enable large economy of scale among network operators, system manufacturers and chip vendors, usually bringing down equipment cost. In addition, 1st gen. systems are characterised by many different technical solutions, making the inter-operator radio co-existence very tricky. On the contrary, a single standardised system solution would realise easy co-existence strongly decreasing needs for guard bands.

Based on that, different standardisation activities have been started in the last few years, in both Europe and United States. In particular, one important project is currently ongoing within ETSI under the label BRAN-HIPERACCESS (HA), ([1], [2]), whose main goal is to specify 2nd generation interoperable BWA systems. HA system is being specified in order to operate at all frequencies between 24 and 44 GHz.

2.2 Architecture

2.2.1 *Background*

In case of a point-to-multipoint cellular radio network using fixed transmission parameters, modulation and coding shall be dimensioned for the worst case path (e.g. AT) in the cell.

In other words, the worst case fading expected for the AT located at the border of the cell will limit the performances of the whole cell population. As coverage performances are usually very important for the operator, a robust modulation scheme coupled with strong Forward Error Correction (FEC) is usually adopted.

Due to cellular reuse, not only the rain-fading margins but also the co-channel interference will contribute to overall link budget. Cell radius reduction, potentially enabling the use of more efficient transmission schemes, wouldn't necessarily insure a better coverage performance: indeed, the higher the modulation efficiency, the higher the Carrier-to-Interference ratio (C/I) requirement, the lower the number of ATs able to operate, for a given service availability.

2.2.2 *Throughput Adaptivity*

In order to solve this problem and achieve main goal of throughput enhancement still maintaining good coverage performances, an adaptive air interface concept has been adopted in HA. According to that, the system shall be able to operate with different transmission modes, featuring different throughputs and requiring different minimum Signal-to-Noise ratios (S/N).

Different physical transmission modes (PHY modes) are selectable, under Access Point Termination (APT) control, to dynamically match the individual link condition of each single AT in the cell. Based on that, the system will be able to efficiently track and counteract changes in available Signal to Noise plus Interference ratio due to rain fades and Interference profiles variations. When link condition for a given AT is degraded, more robust PHY modes will be used on such link, till the situation is improved. Due to the sporadic behaviour of a typical rain fade event, the long-term average throughput experienced by end user will be almost equivalent to the highest mode throughput.

A PHY Mode corresponds to a fixed association between a given modulation scheme and FEC scheme. The adopted modulation belongs to the M-QAM family in both Downlink (DL) and Uplink (UL) directions. M can take up the values 4, 16 and 64 in the downlink direction, 4 and 16 in the uplink direction. The sets of FEC schemes to be supported within HIPERACCESS standard is based on a concatenation between Reed-Solomon Code (RSC) and Convolutional Code (CC).

Mother codes are

- Inner: Convolutional Code with rate 1/2 and constraint length 7, CC(1/2);
- Outer: Reed Solomon Code in GF(2^8), RSC(255,239,8), able to correct up to t=8 byte errors per codeword.

The overall code rate can be varied, in order to be adapted to different constellations and input packet sizes, by puncturing the inner code, from rate 1/2 to rate 7/8 and by shortening the outer code. More details about the FEC schemes adopted in HA can be found in [3], [4] and [5].

Table 2 reports all PHY modes included in present HA specification. For traffic protection, a mandatory set [M1 M2 M3 M4] and an optional set [M1 M2 O3 O4] of PHY Modes are foreseen, to be referred by APT in assigning runtime the transmission mode to be used on a given APT-AT link. Only switching between adjacent modes belonging to the same set is allowed. UL PHY modes correspond to the subset obtained by deleting all modes based on 64 QAM constellation.

PHY Mode C1 is reserved to protect the DL control channel placed at the beginning of each radio frame (Frame Maps), as explained in subsequent session. PHY mode C2 is foreseen for protection of short-signaling packets. Moreover, the more robust traffic PHY mode (M1) will be also used for protecting long-signaling packets.

PHY mode	Modulation	Inner Code	Outer Code	Code rate
C1	4 QAM	CC 1/2	RSC(46,30)	0.32
C2	4 QAM	CC 2/3	RSC(27,11)	0.27
M1	4 QAM	CC 2/3	RSC(228,212)	0.62
M2	4 QAM	-	RSC(228,212)	0.93
M3	16 QAM	CC 7/8	RSC(228,212)	0.81
M4	64 QAM	CC 5/6	RSC(228,212)	0.77
O3	16 QAM	-	RSC(228,212)	0.93
O4	64 QAM	-	RSC(228,212)	0.93

Table 2: PHY modes foreseen in HA.

2.2.3 *Air Interface Structure*

HA is still based on a symmetric 28 MHz single carrier transmission, as for Ericsson 1st gen. system. The symbol rate is 22.4 MHz, and the Nyquist filter roll-off factor is 0.25.

Mandatory duplex method for HA will still be FDD, but an optional Time Division Duplex (TDD) mode is foreseen to cope with situations where spectrum allocation is not enough to cover HA needs.

The mandatory multiple access scheme is TDM for DL and TDMA for UL. An optional TDMA mode is foreseen for DL as well, to support low cost Half-Duplex ATs in case of FDD mode.

A sketch of the Radio Frame structure in case of TDM mode is depicted in figure 2. Radio frame duration is 1ms.

At frame start, a Frame Preamble (FP) of 32 symbols is foreseen to aid frame synchronization and DL carrier acquisition. Two control fields are broadcast in the sector immediately after the frame preamble, with the purpose of communicating to the ATs the structure of next DL and UL frame respectively. The downlink map contains information about positioning of each physical mode in DL, while UL map notifies each AT the transmission starting point and its granted transmission time (if any).

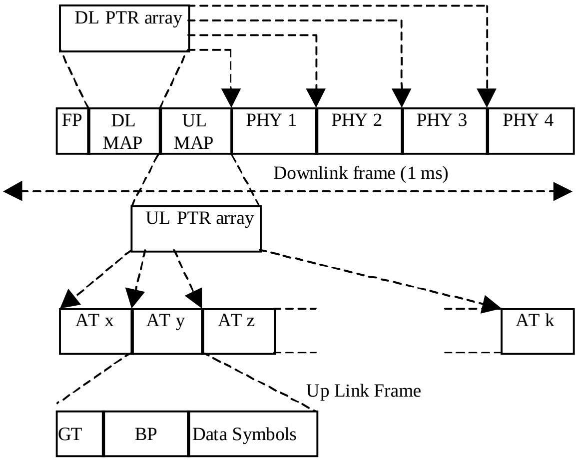

Figure 2: Downlink and Uplink frame structure.

2.2.4 Key Features Summary

Table 3 summarises key features and requirements for HIPERACCESS systems. Optional features are reported in brackets.

Frequencies	*26, 28, 32, 42 GHz*
Channel spacing	*28 MHz, symmetric*
Access Scheme	*DL/UL: TDM(TDMA)/TDMA*
Duplex-Method	*FDD (H-FDD in AT) (TDD)*
DL Modulation	*4 16 (64) QAM*
UL Modulation	*4 (16) QAM*
Nyquist Filter	*SRRC, α = 0.25*
Symbol rate	*22.4 MHz*
FEC	*Concatenated:* *inner Convolutional Code* *outer Reed Solomon Code*
Preamble sizes	*16-32 symbols, CAZAC*
Guard time (UL)	*8 symbols*
Maximum TX power	*+15 dBm*
Minimum RX threshold	*-85 dBm*

Table 3: HA features summary.

2.3 Transceiver Architecture

A conceptual block diagram of the transceiver architecture is sketched in figure 3.

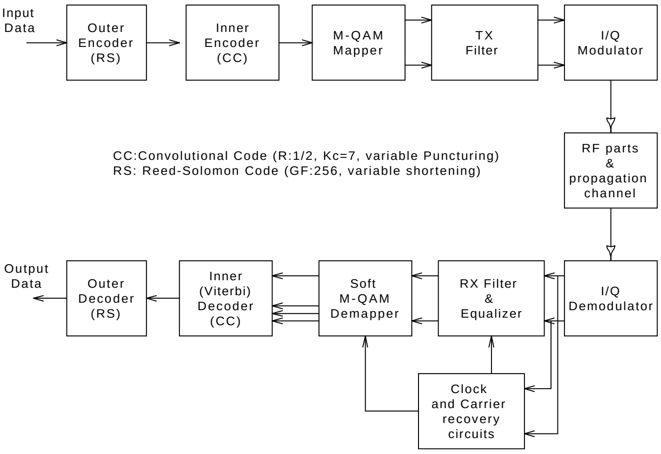

Figure 3: TRX conceptual block diagram.

Digital to analog and analog to digital conversion is done at baseband.

Data symbols are shaped with a Square Root Raised Cosine (SRRC) filter with roll-off factor α=0.25.

The filtered signals are fed to the analogue quadrature (I/Q) modulator and then in the physical channel. This includes analog transmitter parts doing phase noise affected frequency shifting and final amplification (in the transmit side), propagation effects (mainly multi-path fading) and analog receiver parts like low noise amplification, noisy frequency down-conversion (in the receive side).

Final intermediate frequency to baseband signal conversion is done by I/Q demodulator circuitry.

The SRRC receive filter matches the transmit filter.

The decision device must be able to map the received symbols in the M-QAM constellation corresponding to the PHY Mode currently received.

A schematic representation of the digital receiver session, including clock and carrier recovery circuits, is further detailed in figure 4.

A digital adaptive equalizer is used to mitigate effect of intersymbol interference due to frequency selective channels and real hardware. More details about the channel equalizer functionality can be found in [5], chapter 11, [6] and [7].

The carrier recovery phase-locked loop (PLL) loop bandwidth has to be carefully chosen to counteract phase noise and recover residual frequency error due to semi-coherent intermediate frequency to baseband conversion.

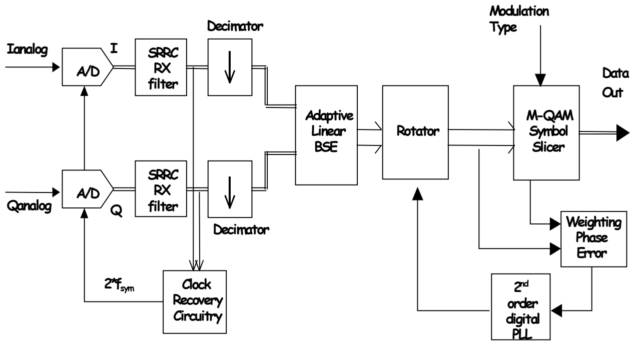

Figure 4: Digital receiver block diagram.

Equalizer and PLL use the difference $e_k = (u_k - \hat{a}_k)$ between decided and received symbol to implement the updating algorithms, assuming that the decided symbol represents the transmitted one, which is almost valid at the Symbol Error Rates (SER) of interest.

A second-order PLL has been adopted, in order to compensate frequency offset as well; in such case the phase estimation φ_k would have a ramp-like behavior. PLL transfer function is the following:

$$A(z) = \frac{a_1}{(1-z^{-1})} + \frac{a_2}{(1-z^{-1})^2} \qquad (1)$$

In the equaliser dimensioning analysis it has been assumed to have neither phase nor frequency error, so that $\varphi_k=0$ and $d_k= u_k$..

The equalizer is an n-taps, adaptive, Baud-Spaced-Equalizer (BSE) described by the following equation:

$$u_k = \boldsymbol{f}_k \boldsymbol{q}_k \qquad (2)$$

In (2) $\boldsymbol{f}_k$ is the n-length complex vector of equaliser coefficient and $\boldsymbol{q}_k$ is the n-length vector of received data samples present in the equaliser shift register, e.g.:

$$\boldsymbol{q}_k = [q_k , q_{k-1} , \ldots, q_{k-l+1}] \qquad (3)$$

The n coefficient values are dynamically updated to minimize the Mean Square Error (MSE), named e_k, caused by fading channel, at sampling time k, (4):

$$e_k = u_k - a_{k-d}, \qquad (4)$$

In (4) u_k is the equalizer output, $a_{k\text{-d}}$ is the transmitted symbol and d is the system delay (see Fig. 3).

The equalizer works in Decision Directed (DD) mode and implements the *stochastic gradient algorithm* to update its coefficients:

$$\boldsymbol{f}_{k+1}=\boldsymbol{f}_k - \delta\,(u_k - \hat{a}_k)\boldsymbol{q}_k^* \qquad (5)$$

In (5) δ is the step size and $\boldsymbol{q}_k^*$ is the complex conjugate of vector $\boldsymbol{q}_k$.

The step size δ determines the algorithm convergence speed to the steady state of the algorithm end the coefficient variance around their mean value. The higher the step size, the faster the algorithm convergence and the higher the coefficient variance at steady state.

2.4 BER Performances

2.4.1 Additive White Gaussian Noise (AWGN) channel

Figure 5 shows the theoretical BER performances of all the PHY modes foreseen and the equivalent Carrier-to-Noise ratio (C/N) values in the following conditions:

- Ø AWGN channel
- Ø No frequency error
- Ø No phase noise
- Ø Ideal carrier recovery
- Ø Non correlated errors at inner decoder output (e.g. infinite length interleaving between inner and outer code).

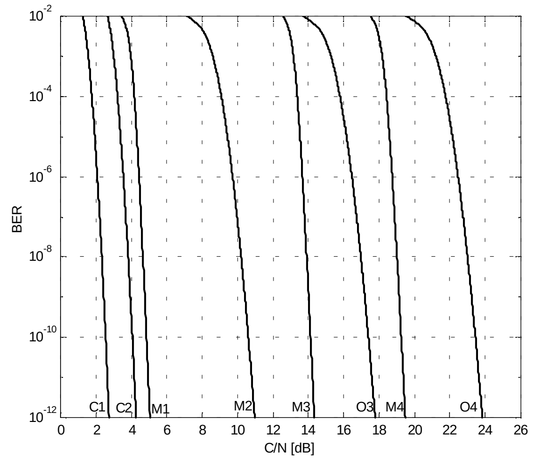

Figure 5: Theoretical BER performance of HA modes.

The requirement about link quality considered has been BER < 10^{-6} for link availability and BER < 10^{-11} for link quality.

FEC scheme C1 allows the DL control field (MAP) to have at least 2dB of extra code gain with respect to the DL PHY mode with the lowest SNR threshold. With such a choice, a virtually error free transmission could be guaranteed for the control information, even when the BER over payload is near the threshold of BER=10^{-6}.

Ideal C/N values of the different Physical Modes are shown in Table 3.

PHY mode	C/N @ BER=10^{-6}	C/N @ BER=10^{-11}
C1	1.9 dB	2.5 dB
M1	4.4 dB	4.9 dB
M2	9.7 dB	10.8 dB
M3	13.7 dB	14.2 dB
M4	18.7 dB	19.4 dB
O3	16.5 dB	17.6 dB
O4	22.5 dB	23.6 dB

Table 4: HA PHY modes performances.

Losses related to practical implementation issues will be considered in the following paragraphs.

HA standard doesn't foresee the presence of an interleaving. Simulations shown that the correlation between errors at Reed-Solomon decoder input decrease the concatenate code performances up to 1 dB @ BER=10^{-6}, as shown for example in figure 6:

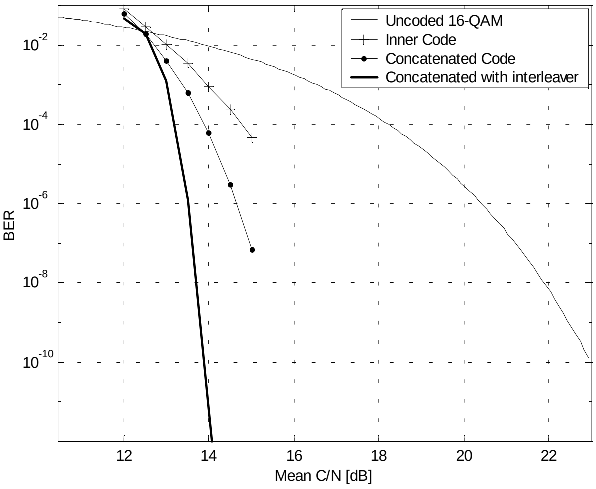

Figure 6: FEC performance with and without interleaving: 16 QAM, inner code: CC(7/8), outer code RSC(69,53,8).

2.4.2 Multi-path Channels

Losses due to no ideal propagation conditions (multi-path channel, amplifier non-linearity, quantization, oscillator phase noise and so on) cause the raw BER to degrade over the ideal one. Anyhow, if uncorrelated errors at the decision device output can be assumed (as in this case), the BER After Correction (BERAC) can be estimated with semi-analytical techniques without the need for time consuming Monte Carlo simulations, used only to verify analytical approach in some reference cases.

For that reason, in most of the analysis carried out only the raw BER curve in the range of interest has been evaluated by simulation.

The adopted powerful error correction codes allow the BER, at the decoder input, to range approximately between 10^{-4} and 10^{-2} while satisfy the required constraints on link BER of (10^{-11} to 10^{-6}), as it can be seen in figure 5.

HIPERACCESS specified multi-path channel models have been considered when defining and assessing equalizer architecture, which are reported in table 4, where T_{sym} is the symbol duration and T_s is the channel impulse response sampling period. More general information about propagation channel models relevant to LMDS systems can be found in [8].

Name	**Equation**
C_1	$H(z) = 0.981 - 0.194 * z^{-2}$
C_2	$H(z) = 0.981 - 0.194 * e^{-j\varphi} * z^{-2}$, $\varphi = \pi * (1 - 1.6 * T_s/T_{sym})$
C_3	$H(z) = 0.895 - 0.447 * z^{-1}$
C_4	$H(z) = 0.895 - 0.447 * e^{-j\varphi} * z^{-1}$, $\varphi = \pi * (1 - 0.8 * T_s/T_{sym})$

Table 5: HA multi-path channels.

In this paragraph equalizer performances at steady state with a fixed fading channel are considered in terms of raw BER. Equalizer coefficients are kept moving around the asymptotic values (e.g. updating logic is not frozen). Perfect synchronization and ideal local oscillators (no phase noise, zero frequency offset and no PLL effects) are also assumed in this first step.

Figure 7 shows the behavior in terms of BER before correction for a 15 taps BSE equalizer with channel C4 and 16 QAM constellation.

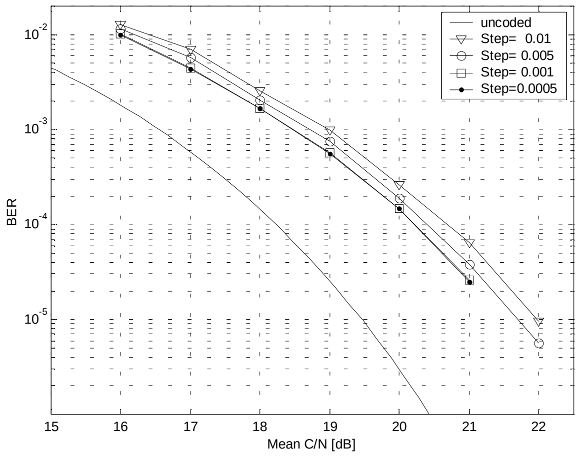

Figure 7: BER performances of a 15 taps BSE equalizer with channel C4, adaptive DD algorithm and different step sizes (16 QAM).

It can be noticed that there is almost no performance degradation for δ smaller than 10^{-3}. A good choice can be to set $\delta = 10^{-3}$, in order to allow the equaliser to efficiently follow slow changes in channel characteristics.

Figures 8 and 9 show the performance of the equalizer in worst-case multi-path channel (C4), considering a different number of taps, for both 16 QAM and 64 QAM constellation.

The minimum number of taps that insures negligible performance loss over an infinite length BSE is n=9 for 16 QAM and n=11 for 64 QAM. Then, in case 64 QAM constellation (optional) is to be supported, the value n=11 should be chosen. On the other hand, as there are no big differences in performances, it could also be possible to reduce hardware complexity and use a 9 taps BSE.

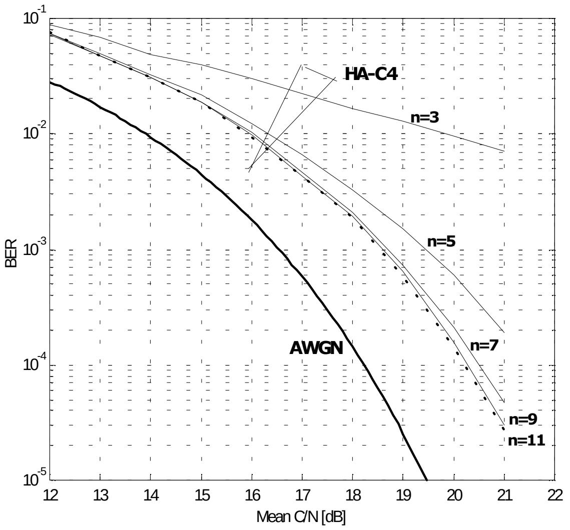

Figure 8: Performances of a BSE equalizer with different number of taps in HA channel C4 compared to AWGN (16 QAM constellation).

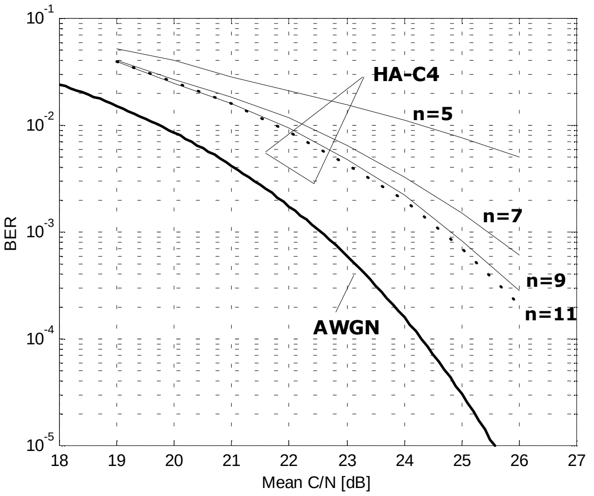

Figure 9: Performances of a BSE equalizer with different number of taps in HA channel C4 compared to AWGN (64 QAM constellation).

Figure 10 shows the performance of the chosen equalizer architecture (DD BSE, 11 taps, $\delta=10^{-3}$) with a 64 QAM modulation in all HIPERACCESS channels.

In the BER range of interest, channel C1 and C2 have almost the same behavior (approximately 0.5 dB loss over a AWGN channel), while the worst case multi-path is clearly represented by channel C4 with approximately 2 dB losses over AWGN channel.

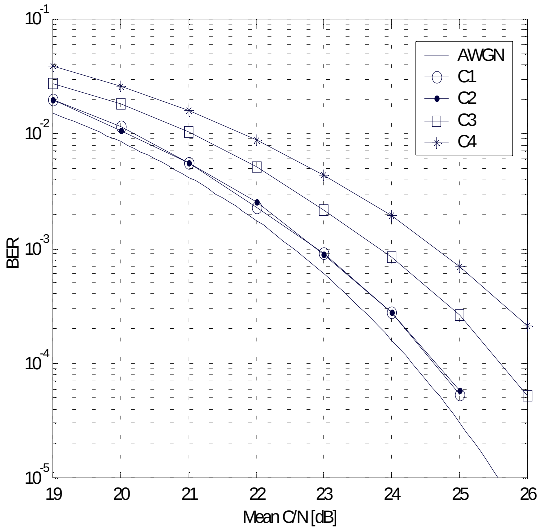

Figure 10: Performances of a BSE equalizer in all HA channels: 11 taps, $\delta=10^{-3}$, 64 QAM constellation.

2.4.3 Performances with Phase Noise

When a real receiver design is considered, carrier recovery PLL must be dimensioned not only for fast tracking of carrier phase and frequency errors, but also to efficiently counteract Local Oscillators (LO) phase noise.

For this reason, overall receiver performances in a phase noise limited environment have been assessed, modeling a system phase noise level of -93dBc/Hz at 100KHz offset from center frequency.

Worst-case carrier frequency error expected in HA has been considered, corresponding to ±10ppm.

Main results of the assessment are reported in figure 11.

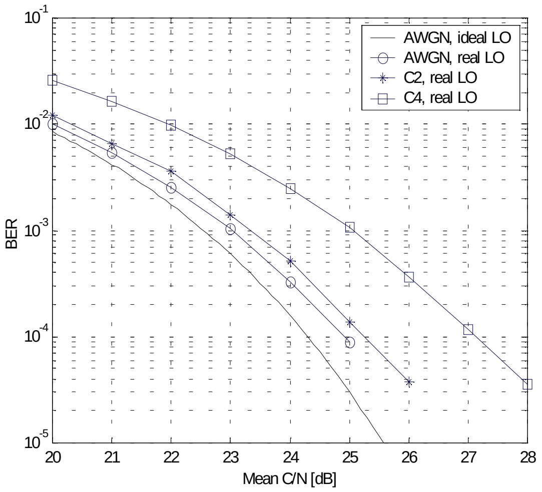

Figure 11: Performance degradation due to phase noise and frequency offsets with different propagation channels for 64 QAM constellation.

A second-order PLL has been adopted, whose 3-dB loop bandwidth was approximately 0.5% of the symbol frequency.

Equalizer parameters used were the ones reported in session 2.4.2.

The constellation considered was 64 QAM.

At raw BER in the range $[10^{-4}\ 10^{-2}]$ following overall losses have been estimated:

- 0.4 to 0.6 dB (AWGN channel)
- 0.7 to 0.9 dB (C2 channel)
- 2.5 to 2.8 dB (C4 channel)

Additional losses due to LO phase noise and frequency offsets (L_{LO}), evaluated over AWGN and HA multi-path channels have been reported.

They are summarized here below:

- $L_{LO} < 0.4$ dB (AWGN, C1 and C2)
- $L_{LO} < 0.6$ dB (C3 and C4)

3. CONCLUSIONS

This paper has dealt with requirements, architectures and performances of 2nd generation BWA systems being specified under label HIPERACCESS.

Focus has been kept mainly on physical layer performances (BER) obtainable with foreseen constellations and error correction schemes, in both AWGN and multi-path channel environments.

Main results about channel equalizer dimensioning and performance degradation in phase-noise limited environment have been also reported, in case a moderate complexity Baud-spaced Equalizer is selected.

4. ABBREVIATIONS

APT	Access Point Termination
AT	Access Termination
ATM	Asynchronous Transfer Mode
AWGN	Additive White Gaussian Noise
A/D	Analog-to-Digital (conversion)
BER	Bit Error Rate
BERAC	BER After Correction
BP	Burst Preamble
BRAN	Broadband Radio Access Networks
BSE	Baud-Spaced Equalizer
BWA	Broadband Wireless Access
CC	Convolutional Code
C/I	Carrier-to-Interference ratio
C/N	Carrier-to-Noise ratio
QPSK	Quadrature Phase Shift Keying
C-QPSK	Constant-envelope QPSK
DD	Decision Directed
DL	Downlink
FDD	Frequency Division Duplex
FEC	Forward Error Correction
FP	Frame Preamble
GT	Guard Time
HA	HIPERACCESS
IP	Internet Protocol
I/Q	In-phase-Quadrature (modulator)
LO	Local Oscillator
LOS	Line Of Sight
MAC	Media Access Control
PLL	Phase-locked Loop
PSTN	Public Switched Telephone Network
PTR	Pointer
QAM	Quadrature Amplitude Modulation
RSC	Reed-Solomon Code
SRRC	Square-root Raised Cosine
STM-x	Synchronous Transport Module-x
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TFM	Tamed Frequency Modulation
UL	Uplink

5. REFERENCES

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