OFDM Point-to-Multipoint Links at ISM 5 GHz Band: Experimental and Analytical Results

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***Abstract*—It is developed a case study, unifying theoretical and practical aspects, concerning planning and implementation of orthogonal frequency division multiplexing (OFDM) point-to-multipoint (PtMp) links at Industrial, Scientific and Medical (ISM) 5 GHz band. The proposed design methodology is validated using analytical results and field measurements.**

***Keywords* – 802.11a; 802.16; link budget.**

I. INTRODUCTION

There has been a huge expansion in Brazilian governmental and enterprise market of point-to-point (to implement backhauls) and PtMp (to distribute traffic among point-of-presences, POPs, and subscribers) wireless technologies. In this arena, wireless metropolitan area networks (WMAN) allow leased wireline replacement. This reduces significantly the capital expenditure/operational expenditure (CAPEX/OPEX) since the wireless infrastructure can be fast deployed at ISM band (regulated by Brazilian National Telecommunications Agency, ANATEL [1]).

We recognize that there is an established knowledge on design of OFDM point-to-point (PtPt) and PtMp links. However, experimental results on broadband wireless networks still have attracted the attention of wireless industry and academy due to continuous evolution of the networks and increasing market demand. Experimental results on PtP links using *Alvarion (www.alvarion.com)* pre-WiMAX (World Interoperability for Microwave Access) equipments are shown in [2]. Performance tests in a WiMAX network loaded with non-real time data and real time video streaming transmission are described in [3]. The authors conclude that it is feasible to obtain high throughput with quality-of-service (QoS) for both traffics, but it is still necessary improvements in mobile environments.

This contribution presents a case study and a design methodology on the implementation of OFDM PtMP links operating at *5 GHz* ISM band. Section II presents the *MetroMax*, a governmental network that we have been planning, implementing and optimizing. Section III describes the physical layer (PHY) of access units (AU) and customer premises equipments (CPE) that we have used in *MetroMax* network. In Section IV, we describe our design methodology, using a case study in order to contextualize it. In Section V we develop a link budget (LB) and validate it by comparing field and analytical results. In Section VI we show field and analytical results on throughput of the scrutinized link. Section VII presents our final remarks.

II – METROMAX NETWORK TOPOLOGY

The field results shown in this contribution have been obtained in a WMAN that uses an *Alvarion* pre-WiMAX proprietary technology operating at ISM *5 GHz* band [5-6]. The *MetroMax* network has been planned, optimized and operated by State Data Processing Company of Rio Grande do Sul (PROCERGS), Brazil. This wireless network connects governmental subscribers to the wireline POP located at PROCERGS headquarters, creating a virtual private network (VPN) based on transmission control protocol/internet protocol (TCP/IP). There are more than *50* active governmental subscribers, referred to fourth trimester (4T) of 2009, such as essential service public providers (e.g., police, fire department, hospitals); state departments (e.g., bureau offices and regulation agencies).

Fig. 1 depicts a simplified block diagram of *MetroMax* network. The PROCERGS headquarters, where there is a POP of private and public networks, is connected to the POP located at the *Administrative Center Fernando Ferrari* (CAFF) building using wireline optical links. This building of *32* floors (*132 m high*) concentrates most of state departments of Rio Grande do Sul, Brazil. The green cloud represents the *MetroMax* wireless POP located at CAFF building. The yellow towers represent AUs used to create sectorized cells that provide PtMp links. The blue tower represents a *20 Mbps* PtPt link, that connects the CAFF POP to the POP located at Police Hill (*287 m* of altitude), where other PtMp links are deployed. There are PtMP links of *2 Mbps*. However, most are *512 kbps* links. This contribution is based on developing activities in order to implement and optimize *54 Mbps* PtMp links.

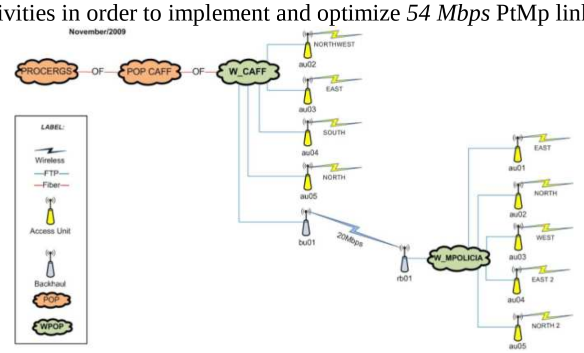

Figure 1. Simplified topology of MetroMax network.

III. PHY DESCRIPTION: BREEZEACCESS VL

The MetroMax network is composed of BreezeAccess VL equipments, manufactured by Alvarion (www.alvarion.com). This platform consists of the following components: CPE BreezeAccess VL subscriber unit (SU); BreezeAccess VL access unit (AU) and sectorized antennas that define the coverage area shape. The PHY and medium access layer (MAC) use a pre-WiMAX proprietary technology strongly based on IEEE 802.11a [4, p. 276].

Tab I shows the eight PHY modes, where for each one it is shown the modulation scheme and convolutional code rate, the gross data rate and the range of the signal-to-interference-plus-noise ratio (SINR) specified by the manufacturer [5, p. 75]. *BpS* means Bytes per Symbol. For instance, the *PHY mode 1* carries *3 BpS* (*6 Mbps* tSymbol/8.0=3 BpS*, where the OFDM symbol length is *4.0* μs).

Tab II shows other relevant PHY parameters [6]. This system supports channel bandwidths of *20 MHz* and *10 MHz* with a maximum number of *11* and *5* non-overlapping channels, respectively, in the *5.8 GHz* band. The bandwidth *W=10 MHz* allows to obtain a net gain in the spectral efficiency using multi-sectorized networks in environments with high level of interference. Notice that this gain occurs even with the reduction of the throughput per sector by a factor of two in relation to that one obtained with *W=20 MHz*.

TABLE I
BREEZEACCESS VL: ADAPTIVE MODULATION AND CODING (AMC) SCHEMES.

PHY m	Modulation	Data Rate	BpS	SINR Range
1	BPSK 1/2	6 Mbps	3	6 dB ≤ SINR < 7 dB
2	BPSK 3/4	9 Mbps	4.5	7 dB ≤ SINR < 8 dB
3	QPSK 1/2	12 Mbps	6	8 dB ≤ SINR < 10 dB
4	QPSK 3/4	18 Mbps	9	10 dB ≤ SINR < 13 dB
5	16-QAM ½	24 Mbps	12	13 dB ≤SINR < 16 dB
6	16-QAM ¾	36 Mbps	18	16 dB ≤ SINR < 21dB
7	64-QAM 2/3	48 Mbps	24	21 dB ≤ SINR < 23 dB
8	64-QAM 3/4	54 Mbps	27	SINR ≥23 dB

TABLE II
BREEZEACCESS VL: PHY PARAMETERS.

Frequency (GHz)	5.725–5.850; 5.47-5.725; 5.15-5.35; 5.03-5.081								
Radio Access	Time Division Duplex (TDD)								
Bandwidth	10 or 20 MHz								
Max. Output Power	AU: -10 dBm to 21 dBm, 1 dB steps								
	SU: -10 dBm to 21 dBm, automatically adjusted by adaptive transmission power control (ATPC)								
Sensitivity (dBm)	PHY	1	2	3	3	5	6	7	8
	Level (20 MHz)	-89	-88	-86	-84	-81	-77	-73	-71
	Level (10 MHz)	-92	-91	-89	-87	-84	-80	-76	-74

IV. DESIGN METHODOLOGY

We have used a design methodology that implements the following procedures: *(1)* to study the technical feasibility; *(2)* to set up the operation frequency; *(3)* to develop a link budget analysis; *(4)* to analyze the performance using analytical and filed measurements. In this section, we shall describe in greater detail the first two steps, while the third and the fourth ones will be described in Sections V and VI, respectively. The case study used to describe and validate the proposed methodology focus, due to space constraints, on just one PtMp link, which connects the 15th Police Station (PS15) to the Police Hill (see Fig. 2).

A. Technical Feasibility

It is used two basic techniques to determine if a specific place can be attended using a given AU. The first one is to locate the subscriber using the *Google Earth Pro* in order to estimate the distances involved and coverage radius. Fig 2 depicts the coverage region (blue lines) using a 90^0 sectorized antenna and estimated link distance (red line). Global Position System (GPS) is used to determine the specific places where the antennas will be installed.

The second procedure consists of using the software *Radio Mobile* to verify if it is possible to implement a line-of-sight (LOS) link. Fig. 3a depicts that it is possible to have LOS from AU (*$30^0$04'46.37"S; 51^0'11'16.20"W*) to CPE (*30^0 03'48.73"S; $51^0$09'32.59"W*). Fig. 3b shows the localization of the AU installed in Police Hill. The heights of the antennas are: *(i)* AU: *45 m* (Fig. 3b); *(ii)* CPE: *7 m* (Fig. 4).

B. Frequency of Operation

The determination of operation frequency is one of the most important aspects when a new link is implemented, mainly in networks that operate in the ISM band, where the co-channel and adjacent channel interference cannot be easily controlled. The Alvarion equipments have a mechanism to operate in promiscuous mode to sound the spectrum [5, p.145].

Figure 2. Link PS15 in the Google Earth Pro.

Figure 3. (a) View from AU antenna located at Police Hill. It is also shown the approximate location of the CPE. (b) Location of AU antenna in Police Hill; (c) Fresnel zone visualized using the *Radio Mobile* software.

Tab. III summarizes some data collected during three hours when the AU was being installed. This table, using the Alvarion CO. definitions [5, p.147], shows the following parameters: *(1)* <u>Channel</u>: frequency of operation in MHz of the sounding channel; *(2)* <u>*Signal Field:*</u> statistics on the number of signals observed in the channel using a power detection scheme. These statistics include the number of signals and the SNIR in dB; *(iii)* <u>*OFDM Field:*</u> statistics on OFDM frames whose preamble can be successfully decoded . These statistics include the number of frames and the average SINR in dB; *(4)* <u>*Noise Floor Field*</u>*:* the average noise floor in dBm calculated for the channel.

TABLE III
DATA RELATED TO THE SPECTRUM SOUNDING AT SUBSCRIBER UNIT.

Channel MHz	Signal Field		OFDM Field		Noise Floor
	Signal	SINR (dB)	Frames	SINR	Power dBm
…					
5655	5216	4	0	-99	10
5600	3975	3	5	-99	8
5665	**1987**	**3**	**0**	**-99**	**8**
5670	481	4	0	-99	21
…					

Analyzing the data shown in Tab. III, the system designer can choose a channel with less interference using the following rules: *(1)* <u>*low counting of OFDM Frames*</u>, choosing if possible channels with value zero to reduce the co-channel interference; *(2)* <u>*low values in the fields associated with Signals*</u> to minimize the interference; *(3)* <u>*low values of Noise Floor*</u> to minimize the interference. It is also necessary to consult the frequency plan to avoid using adjacent channels. The channel *5665* MHz was the chosen channel because it was observed a favorable combination of number of incident signals and noise floor. It is also verified that there is none AU operating using near channels in the adjacent sectors. The channel *5670 MHz* did not present adequate results in relation to the noise floor.

V Link Budget

Tab. IV shows an uplink link budget (LB) for the link PS15.

TABLE IV
Uplink LB for the Link PS15 Shown in Fig. 2.

Line	Symbol	Name	Notes
1	P_{tx}	SU Transmitter Power *(dBm)*	
2	$L_{conc,tx}$	Connectors Loss *(dB)*	0.0 dB
3	$L_{cable,tx}$	Cable Loss *(dB)*	0.0 dB
4	**P_{ir}**	**Power of the Intentional Radiator *(dBm)***	1-2-3
5	G_{tx}	Transmitter Antenna Gain *(dBi)*	21.0 dBi
6	**EIRP**	**Transmitter EIRP *(dBm)***	4+5
7	L_p	Path Loss *(dB)*	Eq. (5)
8	X_σ	Fading Margin *(dB)*	0 to 2.0 dB
9	G_{rx}	AU Receiver Antenna Gain *(dBi)*	19.0 dBi
10	$L_{conc,rx}$	Connectors Loss *(dB)*	0.5 dB
11	$L_{cable,rx}$	Cable Loss *(dB)*	0.18 dB
12	**P_{rx}**	**Received Power *(dBm)***	6-7-8+9-10-11
13	N_o	Noise Spectral Density *(dBm/Hz)*	-174 dBm/Hz
14	W	System Bandwidth dB-Hz	73 dB-Hz
15	F	Noise Figure *(dB)*	3.0 dB
16	**N**	**Noise Power *(dBm)***	13+14+15
17	M_I	Interference Margin *(dB)*	1.0 to 3.0 dB
18	**I**	**Interference-plus-noise power (dBm)**	16+17
19	**SINR**	**Received SINR *(dB)***	12-18

1. It is used the *SU-A-5.4-6-BD-VL* radio from family of equipments *BreezeAccess VL*. The SU has a maximum output at antenna port from *–10 dBm* to *21 dBm* [6].
2-3. The remote radio unit (RRU) is located near the antenna in the SU (see Fig. 4). Therefore, it is assumed that the connectors and cables do not cause any loss.
4. The power output of the intentional radiator refers to the power at the end of the last cable or connector before the antenna.
5. The SU has a directional panel antenna, an outdoor data unit (ODU) responsible for the radiofrequency (RF) signal processing and an internal data unit (IDU) responsible for the baseband signal processing and power supply to the ODU. The integrated antenna, shown in Fig. 4, has the following characteristics: bandwidth between *5.150-5.875 GHz*; azimuth beamwidth (*3 dB*) of 14^0; elevation beamwidth (*3 dB*) of 14^0; gain of *21 dBi* [6]. Fig. 4 also shows the IDU and the peak suppressor.

Figure 4. SU components: panel directional antenna and ODU, IDU, and the peak suppressor.

6. The maximum effective isotropic radiate power (EIRP) is regulated by state agencies, such as Federal Communication Commission (FCC) in the USA and ANATEL in Brazil. The ANATEL *Resolution 506/2008* [1] sets the following limits for the EIRP at 5 GHz ISM band: *(i) 23 dBm* for the bandwidth between *5.150* to *5.350 GHz*; *(ii) 24 dBm* for the bandwidth between *5.470* to *5.725 GHz*. The EIRP is given by (1). Hence, it is used (2) to set the transmitter power to obtain the target EIRP.

$$EIRP = P_{tx} - L_{c,tx} - L_{cable,tx} + G_{tx}. \quad (1)$$

$$P_{tx} = EIRP + L_{c,tx} + L_{cable,tx} - G_{tx}. \quad (2)$$

7. The scrutinized link has a length *(d)* of *3285 meters* (see Fig. 2). Assuming a frequency *(f)* of *5.665 GHz*, the radius of the first Fresnel zone is *6.59 m* (see Eq. 3).

$$r_{in\ meters} = 17.32\sqrt{\frac{d_{km}}{4f_{GHz}}}. \quad (3)$$

It is used the free space propagation model since there is line-of-sight (LOS) between the antennas (see Fig. 3) and the radius of the first Fresnel zone is not obstructed. The free space path loss is given by

$$L_p = 20log\left(\frac{4\pi f}{c}\right), \quad (4)$$

where $c=3.0\ x10^8\ m/s$ is the velocity of light. Using the frequency f in *GHz* and distance *d in km*, then the path loss in dB is given by

$$L(d_{km}) = 92.45 + 20log(d_{km}) + 20log(f_{GHz}). \quad (5)$$

8. Based on our heuristic experience obtained in previous projects, we have assumed that the rain and wind (that could cause a random fading on the received signal) have a minor influence in LOS links whose length is similar to this one. Hence, the random variation of the path loss is modeled using a fading margin X_σ.
9. The AU uses an antenna *AU-Ant-5G-17-90* with the following characteristics: *(i)* bandwidth between *5.150-5.875 GHz*; *(ii)* azimuth beamwidth (*3 dB*) of $90^0 \pm 6^0$; *(iii)* elevation beamwidth (*3 dB*) of 6^0; *(iv)* gain of *19 dBi*.
10. It is used two connectors with loss of *0.25 dB/connector*.
11. It is used the LMR-400 flexible communication cable that has a loss of *35.5dB/100m* at *5.8 GHz*. The length of cable is *0.5 meters*. Therefore, the cables loss is only *~0.18 dB*.
12. The received power as a function of d_{km} is given by

$$P_{rx}(d_{km}) = EIRP - L(d_{km}) - X_\sigma + G_{rx} - L_{conc,rx} - L_{cable,rx}\ . \quad (6)$$

13. The one side noise spectral density N_0 models the additive white Gaussian noise (AWGN) at the receiver input. It is given by

$$N_o = kT_0, \quad (7)$$

where the Boltzmann constant k is equal to *–198.60 dBm/K-Hz*, and T_o is the effective noise temperature in Kelvin (k). Assuming $T_0=270\ K$ (24.31dB/K), then $N_o = -174\ dBm/Hz$.
14. The BreezeAccess VL PHY is based on IEEE 802.l1a PHY that has a bandwidth *W= 20 MHz (73 dB-Hz)*.
15. The noise figure F is defined by the ratio of the SINR at the receiver input to the SINR at the receiver output. It measures the noise introduced by the receiver front-end amplifier. We have assumed a typical value of *3 dB*.
16. The noise power in *dBm* at the detector input is given by

$$N = N_o + W + F. \quad (8)$$

17. The interference margin M_I counts for co-channel interference, non-linear inter-modulation effects, etc. The equipment manufacturer recommends using M_I from *1* to *3 dB* [5, p.74].
18. The total interference-plus-noise in *dBm* is given by

$$I = N + M_I = N_o + W + F + M_I. \quad (9)$$

19. The received SINR is given by

$$SINR = P_{rx} - I. \quad (10)$$

$$SINR = EIRP - L(d_{km}) - X_\sigma + G_{rx} - L_{conc,rx} - L_{cable,rx} - (N_o + W + F + M_I). \quad (11)$$

The maximum cell range d_{km}, to obtain a target $SINR_{rx}$ (and consequently a target data rate according to Tab. I), can be estimated by obtaining $L(d_{km})$ from (11) and then solving (5) as a function of the link distance in kilometres d_{km}.

The ANATEL *Resolution 506/2008* [1] sets the maximum EIRP as *24 dBm* for the bandwidth between *5.470* to *5.725 GHz*. Since the SU antenna has an antenna gain of *21 dBi*, then the maximum transmitter power is *3 dBm*. Using this value at line 1 of the uplink LB, then the estimated *SINR* is equal to *22.95 dB*. Tab. I shows that the minimum *SINR is 23 dB* for PHY 8. Therefore, the dimensioned link ($d_{km}=3.285$) can operate at maximum throughput.

Fig. 5 shows measured and analytical results (**line 12 of LB**) of the radio signal strength indicator (RSSI) in *dBm* as function of the SU transmitted power in *dBm*. The analytical results are parameterized by the fading margin X_σ in *dB*.

Fig. 6 shows measured and analytical results (**line 19 of LB**) of SINR in dB versus the SU transmitted power in dBm. The analytical results are parameterized by the interference margin M_I in dB. It is assumed a fading margin X_σ of *0 dB*. We observe a close agreement between field and analytical results, i.e., the uplink LB is validated. The scrutinized link was tested under a controllable set up (see section VI for details) then it is reasonable to assume interference margin values from *1.0* to *2.0 dB*.

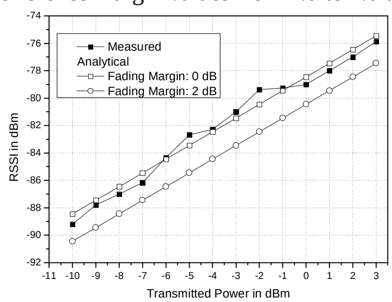

Figure 5. Measured and estimated values for the RSSI in dBm as a function of the transmitter power in dBm.

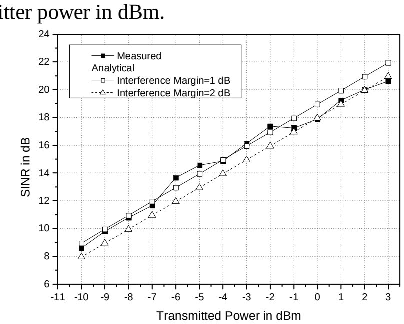

Figure 6. Measured and estimated values for the SINR in dB as a function of the transmitter power in dBm. Fading margin *Xσ=0 dB.*

VI– PERFORMANCE ANALYSIS

A. Analytical Results

We derived in [7] a theoretical MAC and PHY cross-layer saturation net throughput (goodput) model for the IEEE 802.11a standard. It is the same MAC protocol used by *BreezeAccess* equipments, since they use a pre-WiMAX proprietary technology with MAC and PHY protocols based on the standard IEEE 802.11a [4]. Hereafter, we summarize results that allow estimating the goodput for high SINR (i.e., no corrupted frames due to fading). It is assumed the distributed coordination function (DCF) DATA+ACK atomic cycle, as depicted in Fig. 7, where DIFS and SIFS denote the DCF interframe spacing and short interframe spacing, respectively [4, p. 39].

The goodput in *bits per second (bps)* can be defined as the probability that a MAC payload with l_{mac} *octets* be transmitted with success in the average cycle time $\overline{T}$:

$$G = \frac{8 \cdot l_{mac} \cdot \tau}{\overline{T}} = \frac{8 \cdot l_{mac} \cdot \tau}{\overline{B_{tcp,d}} + K_{TCP} \cdot (\overline{B_{tcp,ack}}) + I} . \quad (12)$$

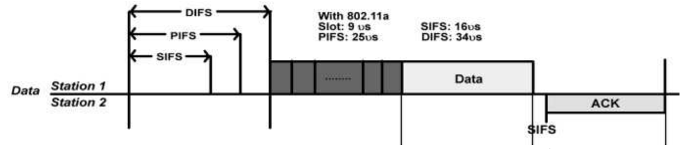

Figure 7. Atomic basic positive acknowledgment (ACK) of data.

The scrutinized link is loaded with just one station (*n=1*) and it is assumed that there is no corrupted frames due to fading, noise and interference (i.e., high SINR). Hence, the average cycle time does not contain terms that model collisions and corrupted frames (see Eq. 19 of [7]). When *n=1*, the probability τ that the STA is transmitting is given by the average minimum contention window (CW) size, where CW_{min} is the minimum CW size (see dark rectangle at Fig. 7).

$$\tau = \frac{2}{CW_{min}+1} . \quad (13)$$

The average busy time to transmit a TCP data segment (*x=d*) and TCP acknowledgment (*x=ack*) when it is used the PHY *mode m* is given by (see Fig. 7):

$$\overline{B_{tcp,x}} = \tau.\left(DIFS + T_{mac,x}(m) + a + SIFS + T_{ack}(m') + a\right) \quad (14)$$

where *a* is the propagation delay. In our case study, *a=3285/c*.

The constant K_{TCP} models the ratio between the number of TCP ACK and TCP data segments. In the test set up, the TCP window size is *8 kbytes* (default) and the TCP payload length *l* is *1024 bytes*. Therefore, $K_{TCP}=1024/8000=16/125$.

The ACK transmission time, whose length is of $l_{ack}=14$ *bytes* [2, p. 80], is given by (15) assuming a *PHY mode m'*. The ACK control frames must be transmitted using the basic service set (BSS) basic rate (i.e. PHY modes 1, 3 and 5) that is less than or equal to the rate of the data frame it is acknowledging. For instance, if a data frame is transmitted at the rate of *54 Mbps* (*m=8*), then the corresponding ACK frame is transmitted at *24 Mbps* (*m'=5*).

$$T_{ack}(m') = tPLCP_{pre} + tPCLP_{sig} + \left[\frac{l_{ack}+(16+8)/8}{BpS(m')}\right] \cdot tSymbol \quad (15)$$

It is used the following notation in (15): *(i)* the physical layer convergence procedure (PLCP) preamble length, $tPLCP_{pre}$, is equal to *12 μs*; *(ii)* PLCP signal field length, $tPCLP_{sig}$, is equal to *4 μs*; *(iii)* OFDM symbol duration, *tSymbol*, is equal to *4 μs* (see Fig. 3 of [7]).

The MAC protocol data unit (MPDU) transmission time when it is used the PHY *mode m* is given by (see Eq. 26 of [7])

$$T_{mac,x}(m) = tPLCP_{pre} + tPCLP_{sig} + \left[\frac{l_{mac}+(16+8)/8}{BpS(m)}\right] \cdot tSymbol . \quad (16)$$

When the client is transmitting a TCP data segment, then the length in octets of MPDU is given by (17), where *l* is the TCP payload, h_{ip} is the length of the IP header in octets ($h_{ip}=5$) and h_{tcp} is the length of the TCP header in octets ($h_{ip}=40$).

$$l_{mac} = l + h_{ip} + l_{tcp} \quad (17)$$

When the server is transmitting a TCP ACK segment, then the length in octets of MPDU is still given by (17) with *l=0*.

The average time that the channel is idle because the STA is in the backoff stage is given by

$$\bar{I} = (1-\tau) \cdot \sigma, \quad (18)$$

where *σ* is the slot time length. The backoff window is decreased by one slot unit each time the channel is declared idle [4, p.43], [7]. The MAC parameters used in Eq. (12-18) are: *slot time σ=9μS, SIFS=16 μs, default DIFS=SIFS+2σ=34μs, default* $CW_{min}=15$ [3, p.143-145]. Observe that these parameters are the same specified at IEEE 802.11a amendment [4, p.297].

B. Field Measurements

The field tests on the link PS15 (see Fig. 2) were performed using the open-source software *Iperf* and the open-source web-based software *Cacti* (configured using the appropriate *Alvarion* radio model). *Cacti* is designed as a frontend to round-robin database tool (RRDtool) that allows a user to poll services at predetermined intervals and plot the resulting data. *Iperf* is a tool to measure TCP throughput and available bandwidth. It implements the technique of *overcastting,* where the transmitter is configured to send saturation traffic (full buffer) and the receiver is configured to collect performance statistics, such as the data rate effectively received and the percentage of lost frames. The AU, located in the Police Hill, was configured as server using the following command: `# iperf –s –D`. The CPE, located at 15th PS, was configured as client using the following command: `# iperf –c 10.0.xx.yy,` where `10.10.xx.yy` is the server IP address.

The MAC and PHY configuration shown in Tab V allows controlling the conditions on which the performance statistics are generated (e.g., the transmission power is set to fixed values disabling the automatic transmission power control, ATPC).

TABLE IV
MAC AND PHY PARAMETERS.

Name	Configuration	Name	Configuration
Modulation and Coding Scheme	Forced to each PHY mode	Frame Retransmission	Disable
Adaptive Modulation	Disable	Burst Mode Transmission	Disable
CPE Transmission Power	Set at fixed values	Frame Concatenation	Disable
Automatic Transmission Power Control (ATPC)	Disable	Packet length	1024 bytes

After configuring the MAC and PHY parameters, the tests are carried out as follows. Firstly, the transmitter is configured to operate using PHY 1. Next, the power is adjusted to a value that does not exceed the maximum value stipulated by the appropriate regulation. In the following, it is generated saturation traffic using the software *Iperf.* The statistics are collected using the software *Cacti*. When the collected statistics converge, the transmission power is decreased and then new statistics are collected. This process continues until the client station (STA) is disassociated due to insufficient received power. This procedure is carried out until all PHY modes are exhausted.

Fig. 8 shows the measured SINR in dB for the different PHY modes (see Tab. I) as a function of the measured time. Observe the SINR decrease for each PHY mode with time due to transmitter power reduction.

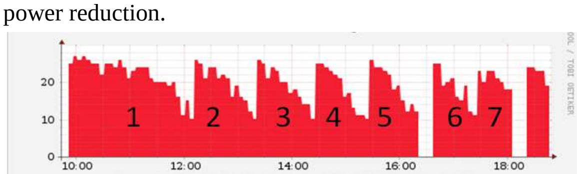

Fig. 8 – Measured SINR in dB for the different PHY modes (black numbers). The abscissa represents the time of the measurement.

Fig. 9 shows the measured throughput as a function of the SINR. We can clearly see the dependence of the maximum net throughput with the SINR, which in its turn depends on the transmitter power. We can also verify that the values of the measured SINR necessary to obtain the maximum throughput are in close agreement with those ones specified in Tab. I. For instance, Tab. I indicates that PHY mode 3 (5) needs a SINR greater than *8 dB* (*13 dB*) while the measured SINR shown in Fig. 9 is around *9.5 dB* (*13.5 dB*).

Fig. 10 shows the measured block error rate (BLER) as function of SINR in dB.

Tab. VI shows that the agreement between the measured and analytical maximum TCP throughput increases with the PHY modes. This occurs because the overhead to transmit ACK control frames becomes more significant for higher data rates. Hence, this dominant effect is highly predominant in relation to other characteristics not taken into account in our *first order theoretical model* (such as buffer management issues).

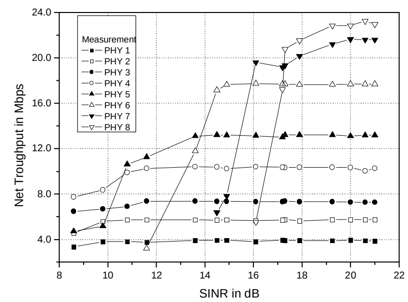

Fig. 9– Measured net throughput versus the measured SINR in dB.

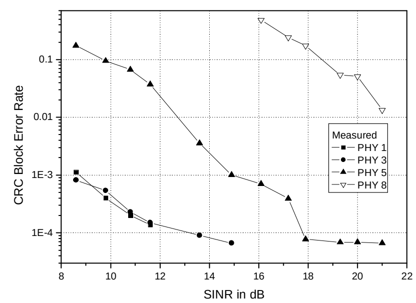

Fig. 10 – BLER versus measured received SINR in dB.

Tab VI – Measured and analytical TCP throughput: l_{mac}*=1024 bytes*.

PHY Mode m	Measured (Mbps)	Analytical (Mbps)	PHY Mode m	Measured (Mbps)	Analytical (Mbps)
1 (6 Mbps)	3.85	4.89	5 (24 Mbps)	13.21	14.63
2 (9 Mbps)	5.75	6.90	6 (36 Mbps)	17.70	18.68
3 (12 Mbps)	7.37	8.79	7 (48 Mbps)	22.05	21.68
4 (18 Mbps)	10.41	11.91	8 (54 Mbps)	23.14	22.91

VII– FINAL REMARKS

We show analytical and field results for OFDM PtMp links operating at ISM *5 GHz* band. From practical point of view, we proposed and validated a design methodology using analytical results and field measurements. From theoretical point of view, we developed a rigorous link budget analysis and analytical results for the saturation TCP throughput. We have been performing strategic studies, out of scope of this paper, that indicate that using wireless technologies instead of leased E1 lines allow an OPEX reduction of *50%* with an increase of system throughput.

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