MICROGRIDS
Large Scale Integration of Microgeneration to Low Voltage Grids

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Coordination:	José Ruela	
Authors:	Jon Anduaga	jon@labein.es
	José Oyarzabal	joseoyar@labein.es
	Sílvio Macedo	smacedo@inescporto.pt
	José Ruela	jruela@inescporto.pt

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Summary

This deliverable is made up of two independent parts that describe the work carried out in WPF.

The first part corresponds to task F2, which was aimed at the "Characterization of the Power Grid as a Communications Infrastructure" and thus covers the topic that is usually referred to as Power Line Communications (PLC).

It includes the characterisation of the communication channel (noise, impedance and attenuation), alternative technical solutions (coding and modulation schemes), PLC Product Suppliers, PLC System Architecture, PLC Related Standards in Europe, and Trial and Commercial PLC.

The second part is dedicated to the MICROGRIDS architecture, and includes the analysis of requirements (from operational, architectural and application points of view), the proposed communications architecture (centered on the TCP/IP family of protocols) and the evaluation of an agents' platform that provides the environment for the execution of the control applications.

Part I – Power Line Communications

1 Introduction

Due to the existing infrastructure, digital communication over the power line has become an excellent opportunity for the energy providers (utility corporations) to implement new services, both for the utilities and for their customers. Digital communications on the low-voltage electrical grid is relevant to a number of industrial actors, such as electricity, gas, heating and water distributors. Typical applications include remote metering reading, remote control tasks, load management, tariff switching, etc.

Since a communication system is always (to a certain degree) designed with respect to the properties of the communication channel, and its operational environment, a basic study of the power line as a communication channel over a broad frequency range (up to 30 MHz) is necessary.

An important property of the electrical signal is its bandwidth (the width of the frequency interval around the carrier frequency that is occupied by the electrical signal), and there exists a close (proportional) relationship between bandwidth and bit rate. Another aspect of fundamental importance that affects the bit rate is the quality of the power line communication channel. Hence, not only the available bandwidth determines the bit rate that can be used, but the quality of the channel also does. However, the available bandwidth is in general the single most important parameter for making high bit rate applications possible.

There are several factors that affect the quality of the power line communication channel. The attenuation of the information carrying electrical signal, as it propagates along the cable, can be too large if the communication distance is too long. Furthermore, the electrical characteristics of the power line between the transmitter output and the receiver input can be modeled as a filter, and this implies that the received signal can be described as a filtered (distorted) version of the transmitted signal. It should be observed that the electrical characteristics of the communication channel depend on the set of loads currently connected to the power line. Hence, these loads also affect the level of signal attenuation and signal distortion.

When evaluating the quality of the communication channel an additional important factor must also be considered; the level, and nature, of the interfering signals that are present at the input of the receiver. If the amount of interfering signals is too large, with respect to the signal distortion, then the receiver will have difficulties to reproduce the original information with sufficient reliability. Several of the interfering signals are generated from the connected loads and, hence, have different origin and characteristics, e.g. periodic signals (related to and/or synchronous with the power frequency), impulse-type signals and noise-like signals, etc.

In chapter 2, important properties of the power line communication channel, and communication system design issues are discussed. In chapter 3 the different technological approaches for broadband power line communication are analysed, paying attention to technical issues of fundamental importance in system design as coding, modulation, adaptation, packet-data transmission. The most important PLC product suppliers are reviewed in chapter 4. Then in chapter 5 a possible system architecture describing the functionality of different components of the PLC system is given. In chapter 6 the applicable European standards produced by standardisation organisations (such as CENELEC, ETSI-PLT and IEC) are reviewed, as well as the actual efforts in standardisation for the 1,6 MHz to 30 MHz frequency range. Finally in chapter 7 the known experience of Power Utilities in running trial and commercial broadband PLC deployments is resumed.

2 Characterisation of the communication channel

The power line was originally designed for distribution of 220/110 Volt power at 50-60 Hz and not for communication purposes; as a consequence, its properties as a communication channel are still not fully understood. Using this medium for broadband communications at higher frequency bands presents many technical problems.

The low-voltage power line network is made of a variety of wiring types, connected in almost random ways (which has a strong effect on impedance mismatch). In addition to that, very different types of devices are part of the LV network (electricity meters, fuses, etc.) and a large variety of appliances can be connected in any point (air conditioners, washing machines, TV sets, etc.)

This type of network has a complex frequency response (amplitude and phase) that changes both in time and frequency. At some frequencies, the received signal can be very strong, while in other frequencies the received signal might be too weak to be usable for reliable data transmission.

The objective of the characterisation of the power line channels is to have a thorough understanding of the complex channel characteristics, and to develop a statistical channel model. Examples of properties that are estimated, based on measurements, are signal attenuation, signal distortion (filtering) and interference characteristics. However, it must also be considered that these properties are not stationary in time since they depend on external actions, e.g., on the set of loads currently connected to the grid. Hence, additional properties that have to be estimated from measurements are the time-variations of the communication channel. An important parameter related to this issue is the length of the time interval where the channel can be regarded as essentially stationary.

Swept frequency measurements indicate that power line channel is a frequency selective medium having high attenuation levels approximately 60 dB over a distance of 200 meters. In a first attempt it is therefore reasonable to model a specific power line communication channel as a liner time-variant filter combined with additive interference.

Figure 1 taken from [5] shows the plot of the frequency response for a sample power line channel. The first graph in the figure represents the power spectral density (psd), of the received signal in dBm/Hz (blue, continuous line), the second graph figure represents the power spectral density (psd), of the noise measured at the receiver, in dBm/Hz (magenta, dotted line). Both graphs are frequency-dependent with peaks and valleys. The shape of the psd of the received signal depends on the distance between transmitter and receiver and on the impedance mismatches along the line, etc. The shape of the noise psd usually has a background component plus several peaks due to broadcast signals, harmonics from switched power supplies, etc.

The most important parameter, from the point of view of data transmission, is the Signal-to-Noise Ratio (SNR), which is the ratio between the desired signal and the interfering noise. Using a logarithmic scale, the SNR is computed subtracting the noise psd from the signal psd. The result can be seen in Figure2.

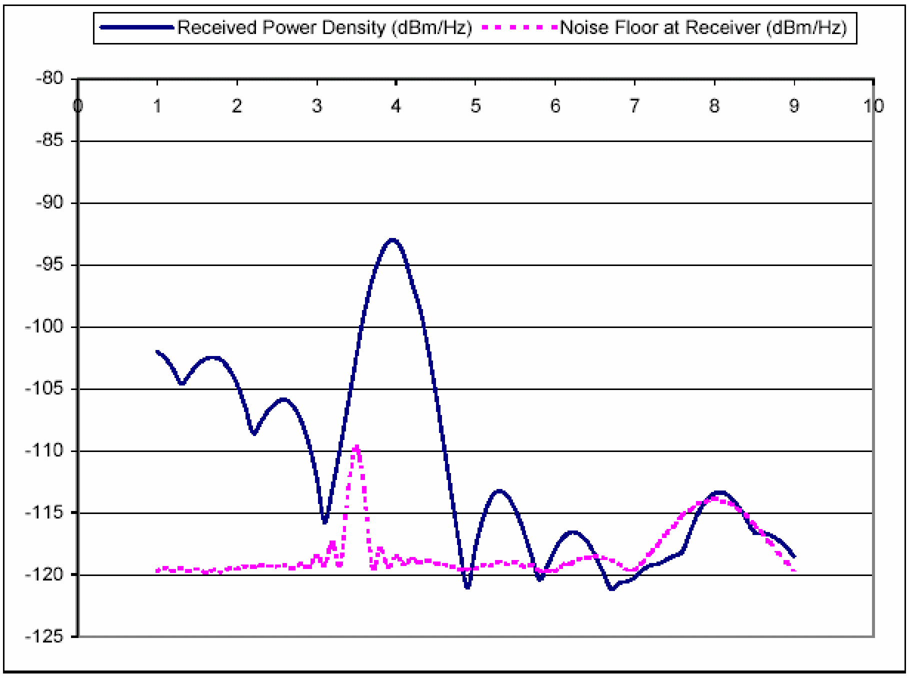

Figure 1: Received Signal and Noise psd.

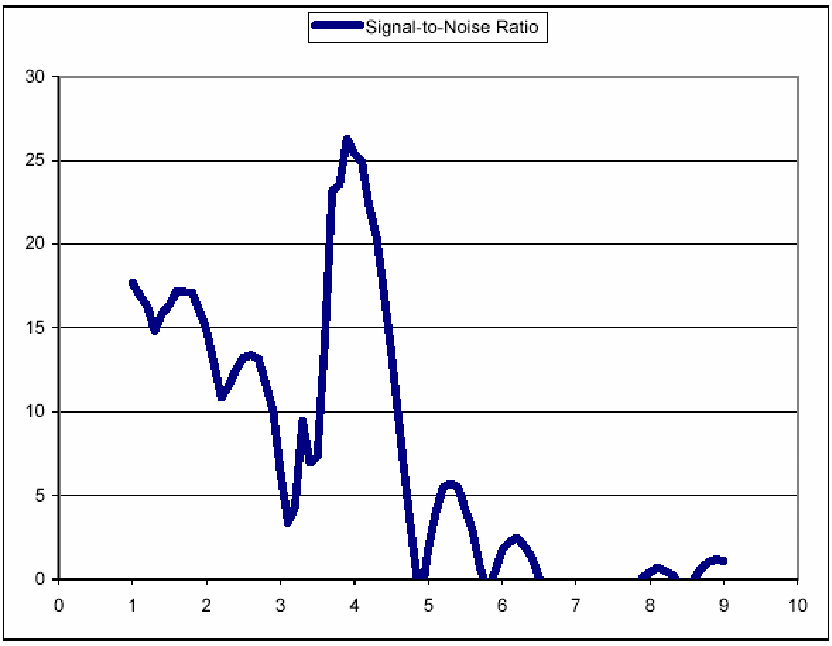

Figure 2: Signal to Noise ratio.

It is well known that the capacity of a communication system is dependent on the SNR. The higher the SNR is, the higher the capacity of the system can be. High system capacities can only be achieved using high-complexity modulations.

In order to communicate reliably on power distribution networks, there are many difficult technical challenges to overcome, such as unstable transmission characteristics, very low impedance channel, etc. Among these technical issues, one of the most important is the design of a communication system that considers the unique features of noise. For the design of appropriate modulation and coding schemes, detailed knowledge of the channel properties in the frequency range up to 30 MHz is essential. Besides signal distortion due to cable losses and multi-path propagation, noise is the most crucial factor influencing digital communications over power-line networks.

2.1 Noise

The noise on power lines is mainly caused by electrical appliances connected to these lines. So the statistical behaviour of this man-made noise is quite different from that of stationary white Gaussian noise, and its characteristics may change in very short time periods. Therefore a model, which can describe the statistics of the instantaneous value of the noise, is needed.

According to different papers, the additive noise in broadband power-line communication channels can be considered as the summation of five noise types, as shown Figure 3.

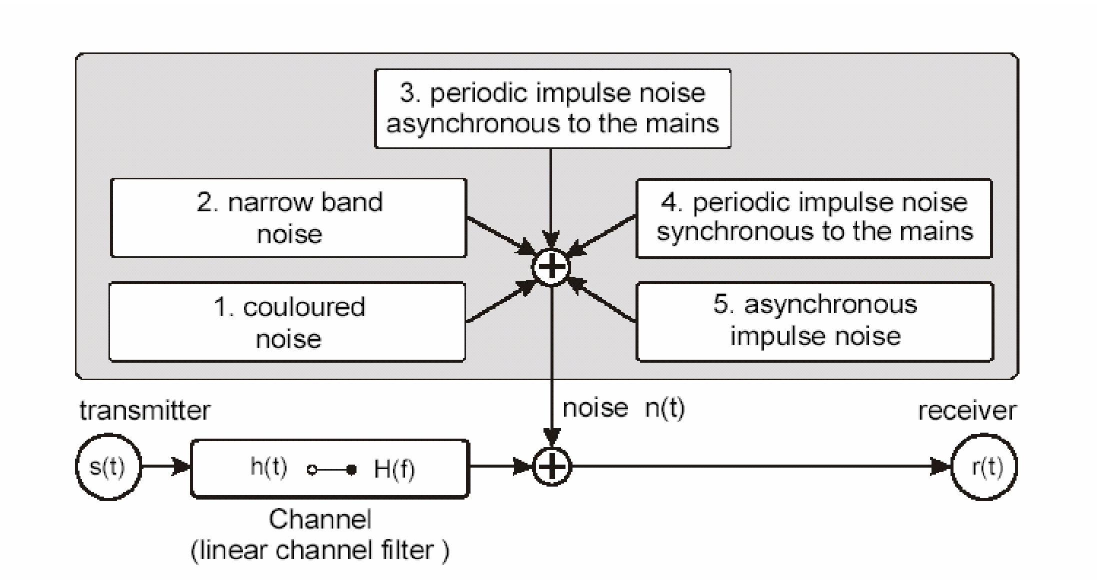

Figure 3: Noise Characterisation.

- Coloured background noise: present over the power-line all the time and mainly occurs due to the distribution transformer, public lighting system and distant loads. Its power spectral density (psd) decreases with frequency. This noise level is higher below 5 MHz compared to the rest of the spectrum. Its level varies slightly over time in terms of minutes or even hours.

- Narrow-band noise: this is noise confined to a narrow portion of the frequency band, over which the level is approximately constant. It mainly occurs due to MW (300 kHz – 3 MHz) and SW (3 MHz – 30 MHz) radio broadcasting signals that are radiated on the power line. This level is generally varying with the time of day (high in the evening and much lower during daylight hours). Normally narrow band noise amplitudes are 10-30 dB above the background noise level in their respective bands. It is observed from measurements that the narrow bands of noise are spread all over the frequency range.
- Periodic impulsive noise, asynchronous to the mains frequency: Most of the time, this type of noise is caused by Switched-Mode Power Supplies (SMPS). These pulses have in most cases a repetition rate between 50 kHz and 200 kHz, which results in a spectrum with discrete lines whose frequency spacing is dictated by the repetition rate.
- Periodic impulsive noise, synchronous to the mains frequency: These impulses have a repetition rate of 50 Hz or 100 Hz and are synchronous to the mains cycle. They are of short duration (some microseconds) and have a power spectral density decreasing with frequency. This type of noise is caused by power supplies operating synchronously with the mains cycle.
- Asynchronous impulsive noise: this type of impulsive noise is caused by switching transients on the network due to switching on/off loads and lightening. These impulses have duration from microseconds to a few milliseconds with arbitrary arrival time. The power spectral density of this type of noise can reach values of more than 50 dB above the background noise.

In order to make the analysis of the noise more clear, a general classification of these types of noise based on their behaviour over time can be done. The first three types of noise usually remain stationary over periods of seconds, minutes or sometimes even for hours, and may be summarised as background noise. The last two types, however, are time variant in terms of microseconds and milliseconds, and can be categorised as impulse noise.

2.1.1 Background noise

As stated above, the background noise comprises coloured noise, narrow band noise and periodic impulsive noise with repetition rates much higher than the mains frequency. A high-resolution spectral analysis of recorded background noise is shown in Figure 4 [1].

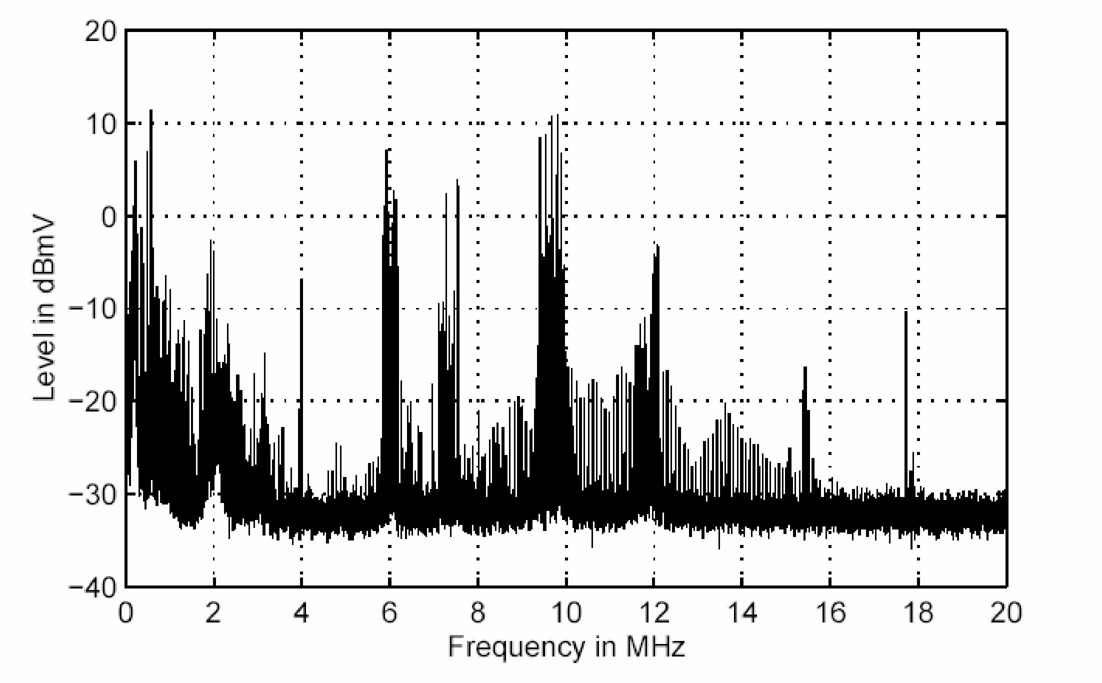

Figure 4: Background Noise.

Especially the (5,95-6,2 MHz), (7,2-7,5 MHz), (9,4-10,2 MHz) and (11,8-12.1 MHz) broadcast bands are quite obvious. But even in the frequency range below 5 MHz most interference can be characterised as narrow-band noise. In the range around and below 2 MHz some coloured noise can be seen, which is above the nearly white quantisation noise. Between 10 and 15 MHz equally spaced lines with varying amplitudes can be detected. A more detailed analysis of these lines reveals a spacing of 100 kHz corresponding to periodic impulse noise with a repetition time of 10 μs.

In some ways, the background noise power spectral density may be considered as constant over different frequency ranges. Hence, the basis of one noise model are sources of white noise which must be defined separately for different adjacent, non-overlapping frequency bands. For each range, the bandwidth and the noise amplitude have to be defined.

2.1.2 Impulsive noise

While background noise is stationary over seconds, minutes or even hours, the short time variance in the power line environment is mostly introduced by impulsive noise caused by switching transients.

Typical asynchronous impulse events are caused by switching transients anywhere in the power-line network. They often have a shape similar to damped or overlaid damped sinusoids.

The medium power spectral density of a typical impulse noise is shown in Figure 5.

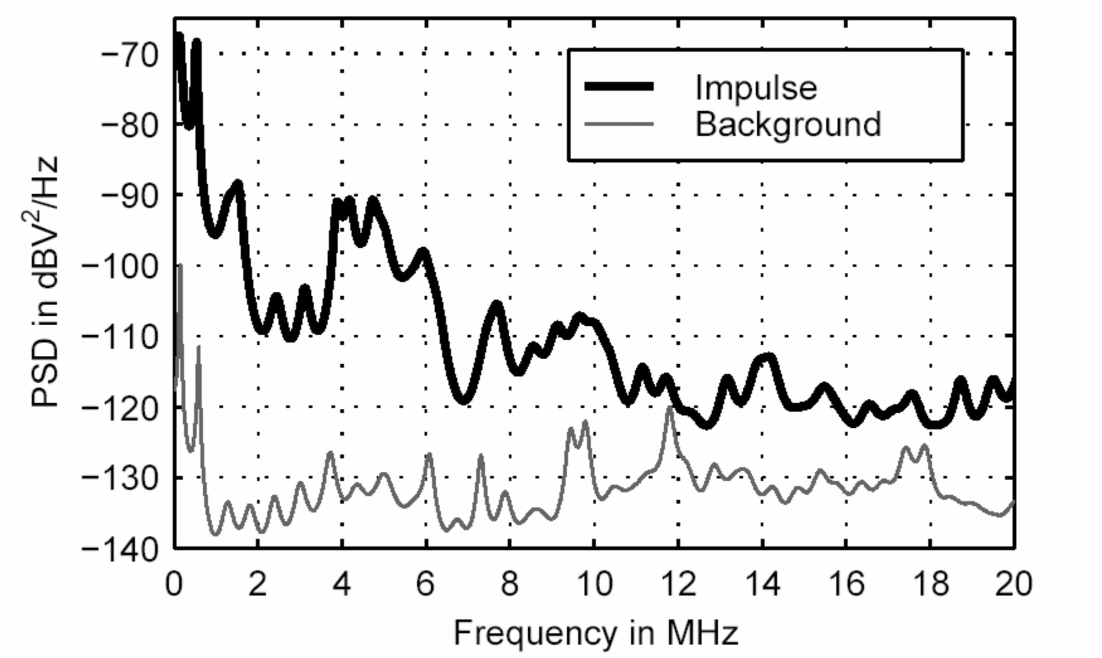

Figure 5: Impulsive and Background Noise.

The power spectral density due to that impulse exceeds in the whole frequency range the psd of the background noise for at least 10-15 dB. In certain frequency bands it exceeds the background noise by more than 50 dB. The spectral power is concentrated in certain frequency ranges. The maximum value is below 1 MHz.

The average psd of an impulse noise, as plotted in Figure 5, gives an idea of the actual change in the noise scenario during the occurrence of such noise impulse. The psd of the background noise measured at the same location is also plotted in Figure 5.

The values of the characteristic parameters of the impulse examples indicate a high likelihood of bit or even burst errors for digital communications over power lines, caused by impulse events.

According to the measurements, the periodic impulsive noise synchronous to the mains frequency has a psd decreasing with frequency and some microseconds of duration. Because the short duration, these noise impulses can not introduce any error in the interpretation of an OFDM symbol, which has a duration of 500 µseconds. However, the noise duration of asynchronous impulsive noise can reach several milliseconds with a psd up to more than 50 dB above the background noise.

2.1.2.1 Impulse noise characteristics

Due to the high impact of impulse noise on data transmission it is essential to gain statistical information about the probability distribution of impulse amplitude, impulse width and interarrival time (distance between two consecutive impulses). The curves of different measurements show the distribution of these three variables. The amplitude distribution is represented in Figure 6. It shows that about 90% of the detected impulses have an amplitude between 100mV and 200mV. Only less than 1% exceeds maximum amplitude of 2 V.

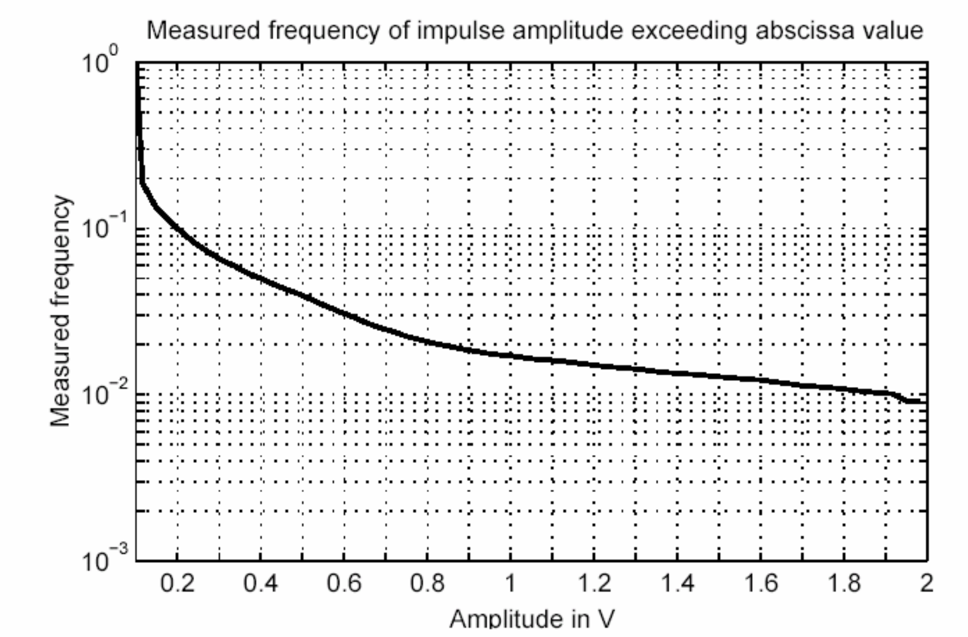

Figure 6: Amplitude Distribution of impulse noise.

In Figure 7 the measured width of the impulse width is shown. It is obvious that during that measurement only about 1% of the impulses have a width exceeding 500 µs and only 0.2% exceeds 1 ms. The largest detected impulse width is about 5,7 ms.

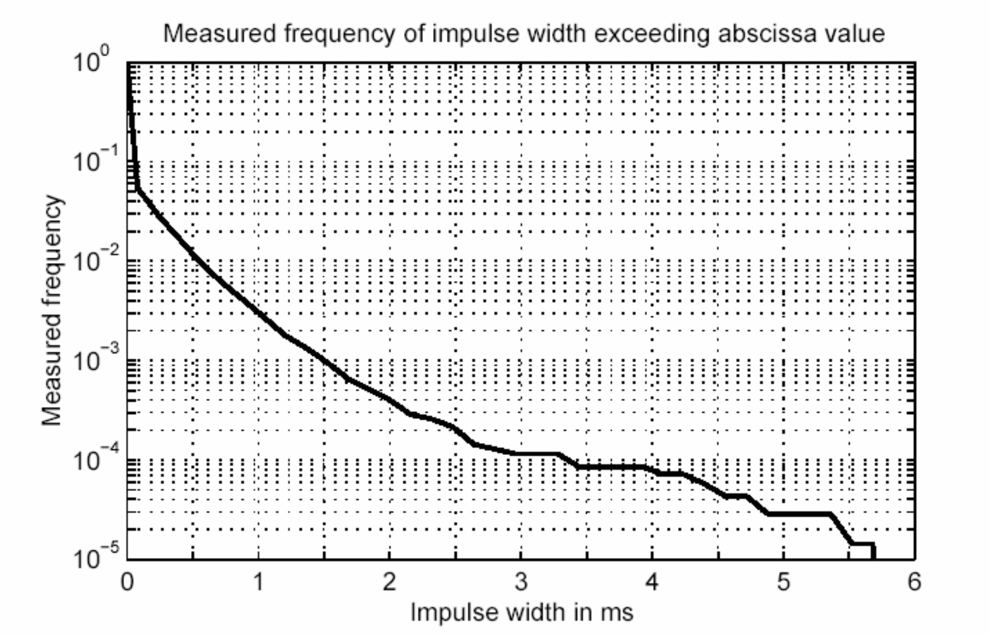

Figure 7: Width Distribution of impulse noise.

The distribution of the measured interarrival times is shown in figure 8.

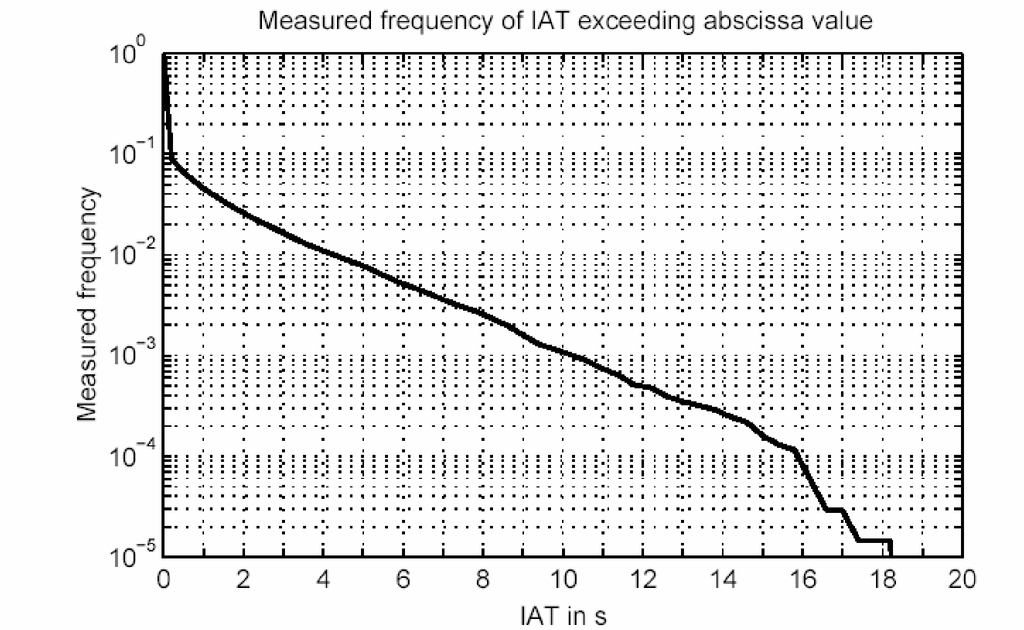

Figure 8: Frequency Distribution of impulse noise.

More than 90% of the recorded interarrival times were below 200 ms. More detailed investigation reveals that about 30% of the detected impulses have an interarrival time of 10 ms or 20 ms pointing to periodic impulses synchronous to the mains frequency. Besides that, many recorded interarrival times were below 5 ms due to burst-like impulsive events.

2.2 Impedance

A power line has highly variable impedance depending on several factors such as its configuration (star connection, ring connection) or the number of appliances linked.

Extensive data on this subject has been published by Malack and Engstrom of IBM (Electromagnetic Compatibility Laboratory) [2], who measured the RF impedance of 86 commercial AC power distribution systems in six European countries (see Figure 9).

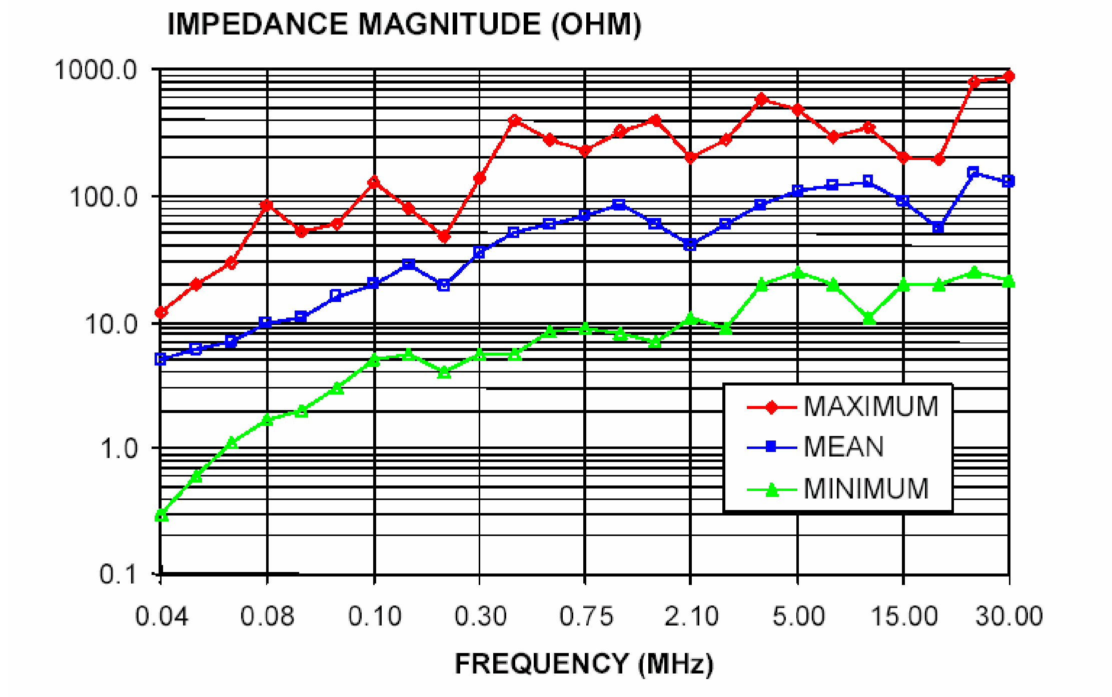

Figure 9: RF Impedance of a power line.

These measurements show that impedance of the residential power circuits increases with frequency and is in the range of about 1,5 to 8 Ω at 100 kHz. It appears that impedance is determined by two parameters: the loads connected to the network and the impedance of the distribution transformer. In the last period a third element influences in a relevant way the impedance of a power line, in particular in the residential network. It is represented by the EMI filters mounted in the last generation of home appliances (refrigerators, washing machines, television sets, hi-fi). Wiring seems to have a relatively small effect. The impedance is usually inductive.

For the compliance tests the normative EN50065 uses two artificial mains networks conforming to sub-clause 11.2 of CISPR 16-1: 1993. Measurements of real networks have shown that this artificial network does not truly represent practical network impedance. To better evaluate the performance of a real signaling system an adaptive network has to be used in conjunction with the CISPR 16-1 artificial network. The design of the adaptive circuit is included in the informative annex F of EN50065-1 (revision 2001).

2.3 Attenuation

The propagation and attenuation of high frequency carrier signal are very dependent upon the power line structure, current variation, and loads, among other things. Moreover, the characteristics are not well defined since the electrical and impedance characteristics of electric power circuits are very complicated to analyse. Therefore, the influence of load at home and office on the quality of the PLC communication channels can be only realistically understood by actual measurements of the high-frequency attenuation characteristics.

A relatively recent study to measure the attenuation of high-frequency signals over power line was the one directed on power transmission and distribution lines [3]. In this study, on a de-energised 15 kV power distribution line, the attenuation and characteristic impedance were found to be relatively constant at frequencies between 15 and 30 MHz, with minimal influence from line geometry and power equipment placement.

3 Alternative Technical Solutions

A general rule for system design is that an efficient communication system should be tailored to the properties of the communication channel. As a consequence, if the fluctuations of the channel quality are large, then it might be motivated to be able to adapt to changing channel conditions. To be able to do this, the communication channel behaviour has to be known. One possible strategy to be used is described next:

- A well-defined measuring signal is first sent to the receiver, and the receiver then calculates an estimate of the channel filter function.
- Furthermore, during a time interval with a silent transmitter, the receiver can estimate the characteristics of the interference (noise).
- Since the transmitter is designed to adapt, this information is sent back from the receiver to the transmitter, followed by a joint agreement of how to most efficiently communicate over the current communication channel.

The advantage of such an adaptive structure is the potential of efficient communication over a wide range of channel conditions. Typically, good channel conditions imply relatively high information bit rates and modest coding, whereas significantly reduced bit rates combined with powerful codes are used for low-quality channels. The adaptive structure outlined above contains some implicit assumptions regarding a stationary channel during the time interval corresponding to the channel measuring and the transmission of data. Therefore a mechanism for supervision of significant changes in channel characteristics should also be implemented.

An alternative important design philosophy is to focus on less adaptable but robust communication systems. In this case both transmitter and receiver are designed for reliable communication over a broad range of channel conditions. However, the transmitter is fixed in this case, and only the receiver adapts to different channel conditions. The price paid for robustness is in general a relatively low bit rate, compared with the bandwidth used. Very robust communication can often be established with so-called spread spectrum techniques. Robustness is here obtained by using large frequency diversity and, hence, the cost of this method is a significant increase in bandwidth consumption.

Although it is true that an adaptable communication system is technically more complex that a fixed one, it should be observed that adaptation is mainly a matter of different software configurations. Furthermore, since the cost for fast signal processing steadily decreases, an adaptive structure should at least be considered, due to its potential of better communication performance, and also due to its potential to adapt to future needs.

There are also several additional technical issues of fundamental importance in system design as: coding, modulation, packet-data transmission, etc.

All the negative characteristics of the power line push to consider modulation techniques that effectively combat such a hostile environment. Among them, the most popular are CDMA (Code Division Multiple Access) and OFDM (Orthogonal Frequency Division Multiplexing). Within CDMA, two techniques are appropriate: one is Multi Carrier MC-CDMA, that uses more carriers and thus more frequency channels for multiple access purpose, and the other is Direct Sequence DS-CDMA, where only one carrier is used and the different users are separated by orthogonal codes. The OFDM technique employs inverse Fourier transformation to spread the transmitted signal spectrum coping with frequency selective fading and impulsive noise.

These techniques are real candidates for future broadband PLC since they permit:

- to separate overall transmitted data in many parallel independent sub-streams,
- to implement flexible resource management strategies in order to cope with channel impairments,
- to provide fine granularity in multimedia services by supporting variable data rates,
- and to achieve remarkable capacity.

3.1 DS-CDMA

DS-CDMA is a spread spectrum based technique. Spread spectrum refers to modulating a signal for the purpose of spreading its energy across a frequency range that is wider than its original unmodulated bandwidth. A block diagram shown in Figure 10 illustrates the basic elements of a spread spectrum digital communication system.

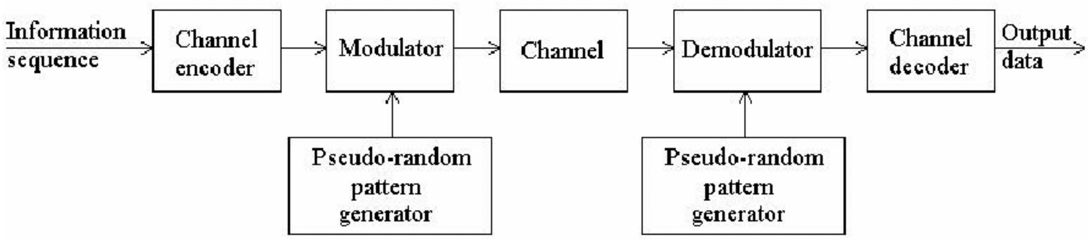

Figure 10: DS-CDMA Block Diagram.

In the modulator, two modulation techniques are considered, Phase Shift Keying (PSK) and Frequency Shift Keying (FSK). PSK is appropriate in applications where phase coherence between the transmitted and the received signal can be maintained over a time interval that is relatively long compared to the reciprocal of the transmitted signals bandwidth; PLC is an application of this type. FSK modulation is used where such phase coherence cannot be maintained; a good example for this application is communication between high-speed aircrafts.

In PSK modulation, the pseudo-random sequence generated at the modulator is used to shift the phase of the PSK signal pseudo-randomly. The resulting modulated signal is called a Direct Sequence (DS) spread spectrum signal. The name Code Division Multiple Access can be understood now easily: each user has an individual pseudo-random sequence, an individual code, and all the users are distinguished by this code.

At the FSK modulation, the pseudo-random sequence selects the frequency of the transmitted signal pseudo-randomly so that the signal occupies a frequency slot for a short time before hopping to another slot in a pseudo-random order. The resulting signal is called a Frequency Hopped (FH) spread spectrum signal. The random nature of the sequence evenly distributes the hopped frequency band across the expanded spectrum.

Generally, a spread spectrum technique can be used for three purposes:

- to combat or suppress the detrimental effects of interference due to jamming, interference coming from other users of the channel and self interference due to multi-path propagation,
- to hide a signal transmitting it at low power, and thus, making it difficult for an unintended listener to detect in the presence of background noise,
- to achieve message privacy in the presence of other listeners.

The detrimental effect mentioned in the first aspect is really typical of the power line medium. In this case the "jammer" is the high amplitude sinusoid signal used for transmitting the power. Because all the communicators use the same medium and frequency range, the interference coming from other users must be seriously taken into consideration. Suppressing the reflections at the connection point or using the MC-CDMA modulation technique can decrease the interference originating from multi-path propagation.

3.2 OFDM

OFDM is also a spread spectrum technique for transmitting messages simultaneously through a linear band limited channel without InterChannel and InterSymbol Interference (ICI and ISI) using multi-channel transmission. This can be solved using discrete Fourier transform to perform baseband modulation and demodulation and using both a guard space between the symbols and a raised-cosine windowing in the time domain. The ICI can be reduced to zero by introducing the Cyclic Prefix (CP) or cyclic extension that solves he problem of orthogonality between each subchannels (subcarriers). This denotes that the guard space is filled with a cyclic extension of the OFDM symbol. This effectively simulates a channel performing cyclic convolution, which implies orthogonality over disperse channels when the CP is longer than the impulse response of the channel.

The above mentioned narrowband subchannels experience almost flat fading, which makes equalisation very simple. To obtain high spectral efficiency the frequency response of the subchannels are overlapping and orthogonal, hence the name OFDM. This orthogonality can be completely maintained, even though the signal passes through a time-disperse channel, by introducing the cyclic prefix. This could be a copy of the last part of the OFDM symbol that is pre-pended to the transmitted symbol. This makes the transmitted signal periodic, which plays a decisive role in avoiding ICI and ISI. A model for an OFDM system is depicted in Figure 11.

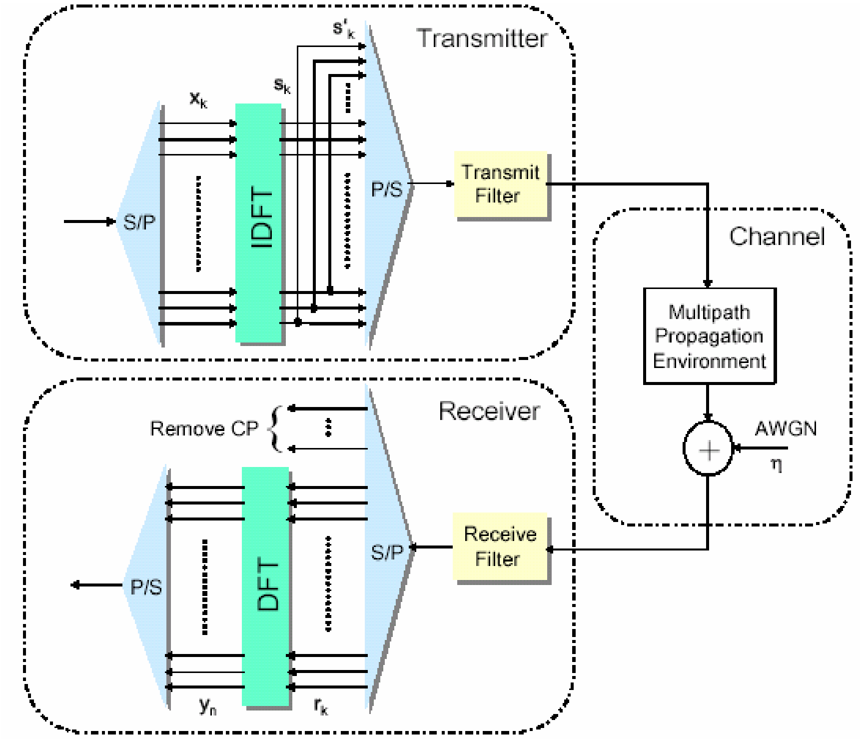

Figure 11: OFDM Block Diagram.

OFDM is not a new technology, and is being used in many other communication systems as ADSL, VDSL, DAB (Digital Audio Broadcasting), and DVB (Digital Video Broadcasting), to name a few. Using OFDM has allowed companies with these technologies to obtain high data rates in adverse conditions. Specifically, OFDM is very robust against frequency selective fading channels and large time spreads. It is a special case of multi-carrier transmission that uses several sub-carriers to communicate. It is both a modulation and a multiplexing technique. Using 1000 channels or more gives the flexibility that if a carrier is working in a space with a lot of interference on that carrier, then it can be disregarded while transmission continues on the remaining carriers thus avoiding this interference and ensuring reliable communications.

The typical frequency division data system divides the frequency band into N non-overlapping frequency channels, as shown in Figure 12 (a). Because there is no overlapping, there is no inter-carrier interference. The disadvantage of this system is inefficient use of the spectrum.

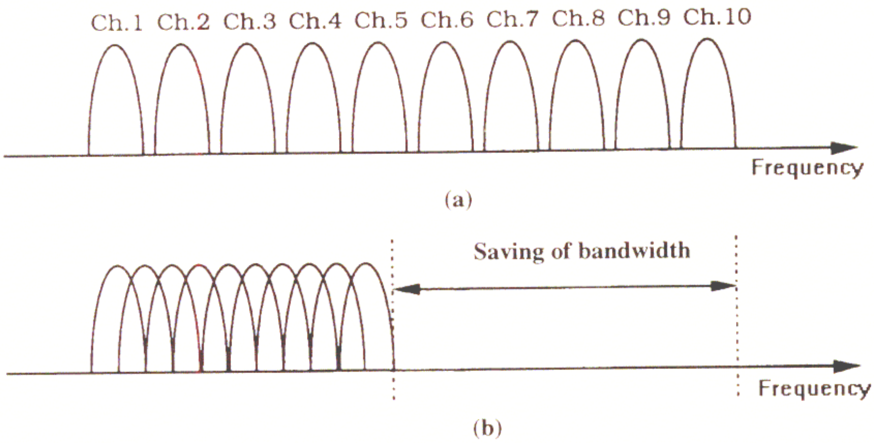

Figure12: Overlapped frequency channels.

On the other hand OFDM uses overlapped sub channels, as in Figure 12 (b), in a way that guarantees orthogonality between different modulated carriers. The orthogonality causes the carriers to be linearly independent and carrier spacing to be a multiple of 1/T. A whole number of cycles of other carriers in the symbol period T implies that there is no contribution from all but one carrier at the integration.

Fast Fourier Transform can be used to obtain the contribution of a carrier without cross talk; there is no need for sub-carrier oscillators. OFDM is a sum of sub-carriers that are modulated using any well-known modulation methods, like Phase Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM).

The main advantages of OFDM are:

- Efficient in multi-path fading channels with large time spreads, i.e. power line.
- Data rate per sub-carrier is adaptable (according to the SNR detected at this sub-carrier).
- Interferences only affect some carriers while the remaining carriers ensure reliable communications.
- The effect of impulsive noise (very common in power line environments) is reduced due to the long symbol time compared to the short duration of the impulsive noise.

Thus, in summary, the use of OFDM modulation allows PLC technology to obtain speeds of up to 45 Mbps (27 Mbps downstream and 18 Mbps upstream). With this technology the optimization of the bandwidth is maximized, assuring that each active user is getting the best performance all the time.

3.3 MC-CDMA

This technique – Multi Carrier Code Division Multiple Access – is a combination of DS-CDMA and OFDM; it also uses Fast Fourier Transform for signal transmission and reception; and thus it is robust to the frequency selectivity of the channel.

In order to see the difference between MC-CDMA and OFDM, now we discuss a complete MC-CDMA system. The transmitter spreads the original signal using a given spreading code in the frequency domain. In other words, a fraction of the symbol corresponding to a chip of the spreading code is transmitted through a different subcarrier.

For Multi-Carrier transmission, it is essential to have frequency nonselective fading over each subcarrier. Therefore, if the original symbol rate is high enough to become subject to frequency selective fading, the signal needs to be Serial-to-Parallel (S/P) converted first before being spread over the frequency domain. The basic transmitter structure is similar to a normal OFDM scheme; the only difference is that the MC-CDMA scheme transmits the same symbol in parallel through many subcarriers, whereas the OFDM scheme transmits different symbols. Figure 13 shows the MC-CDMA transmitter.

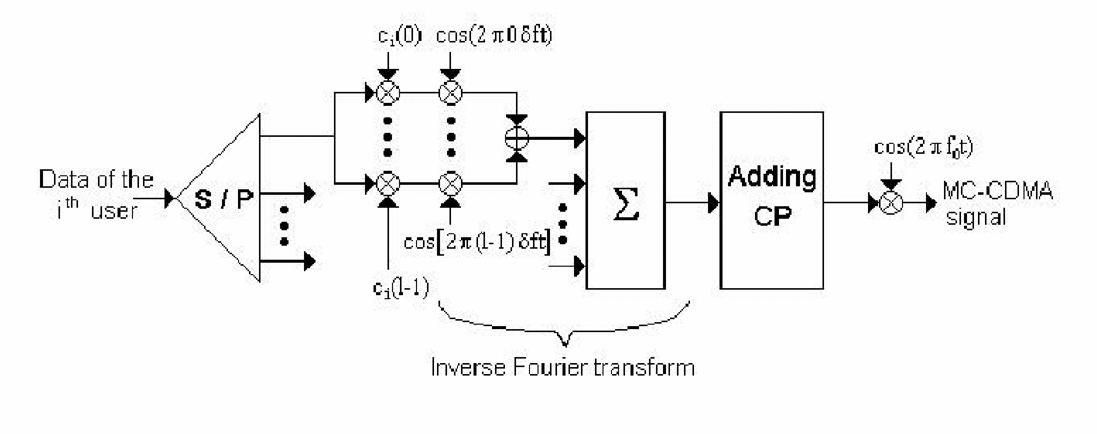

Figure 13: MC-CDMA Transmitter Block Diagram.

3.4 GMSK

Gaussian Minimum Shift Keying is a special form of narrow band modulation. GMSK is a simple yet effective approach to digital modulation for wireless data transmission. To provide a good understanding of GMSK, a review of the basics of MSK (Minimum Shift Keying) will be given.

The Fourier series expansion of a NRZ data stream shows harmonics extending to infinity. Hence, an unfiltered NRZ data stream used to modulate a RF carrier will produce a RF spectrum of considerable bandwidth. Of course, there are strict regulations about spectrum usage making the use of such a system impractical. A possible solution is starting to remove the high frequency harmonics from the Fourier series by passing the data signal through a low pass filter. This suggests that pre-modulation filtering is an effective method for reducing the occupied spectrum in wireless data transmission. In addition to compact spectrum, a wireless data modulation scheme must have good bit error rate (BER) performance under noisy conditions.

The fact that GMSK uses a two-level continuous phase modulation (CPM) format has contributed to its popularity. Another point in its favour is that it allows the use of class C power amplifiers (relatively non-linear) and data rates approaching the channel bandwidth (dependent on filter bandwidth and channel spacing).

Before discussing GMSK in detail it is convenient to review MSK, from which GMSK is derived. MSK is a continuous phase modulation scheme where the modulated carrier contains no phase discontinuities and frequency changes occur at the carrier zero crossings. MSK is unique due to the relationship between the frequency of a logical zero and one: the difference between the frequency of a logical zero and a logical one is always equal to half the data rate. In other words, the modulation index m is 0,5 for MSK, as defined by:

$$m = \Delta f \,.\, T$$

where

$$\Delta f = |f_{logic\ 1} - f_{logic\ 0}|$$

$$T = 1/\text{bit rate}$$

For example, a 1200 bit/s baseband MSK data signal could be composed of 1200 Hz and 1800 Hz frequencies for a logical one and zero, respectively.

Baseband MSK is a robust means of transmitting data in wireless system where the data rate is relatively low compared to the channel bandwidth. An alternative method for generating MSK modulation can be realised by directly injecting NRZ data into a frequency modulator with its modulation index set for 0,5. This approach is essentially equivalent to baseband MSK.

The fundamental problem with MSK is that the spectrum is not compact enough to realise data rates approaching the RF channel bandwidth. A plot of the spectrum for MSK reveals sidelobes extending well above the data rate (see Figure 14). For wireless data transmission systems that require more efficient use of the RF channel bandwidth, it is necessary to reduce the energy of the MSK upper sidelobes.

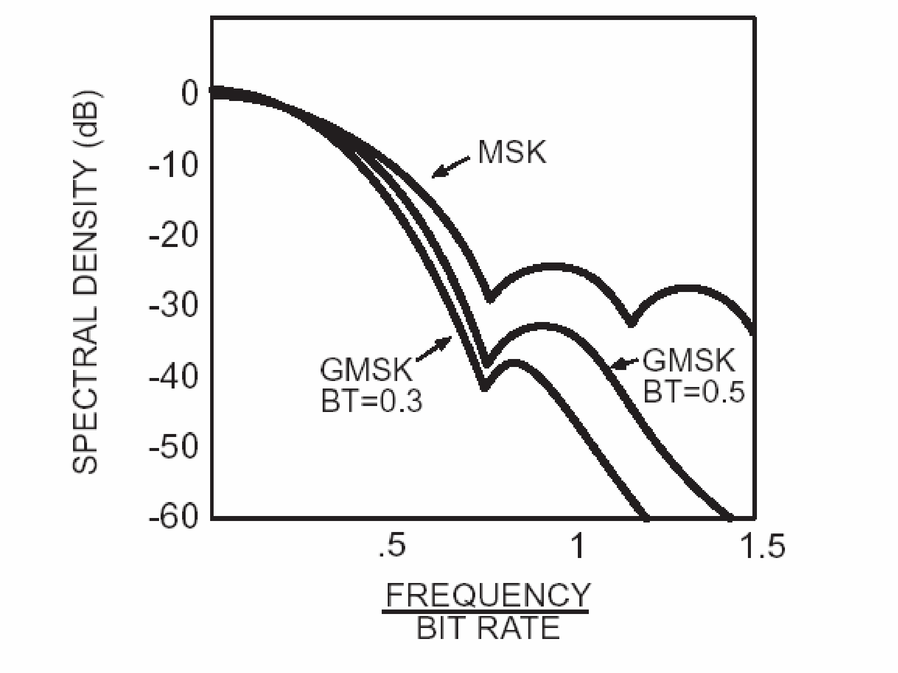

Figure 14: Spectral density for MSK and GMSK.

The straightforward means of reducing this energy is low pass filtering the data stream prior to presenting it to the modulator (pre-modulator filtering). The pre-modulation low pass filter must have a narrow bandwidth with a sharp cut-off frequency and very little overshoot in its impulse response. This is where the Gaussian filter characteristic comes in. It has an impulse response characterised by a classical Gaussian distribution (bell shaped curve), as shown in Figure 15. Notice the absence of overshoot.

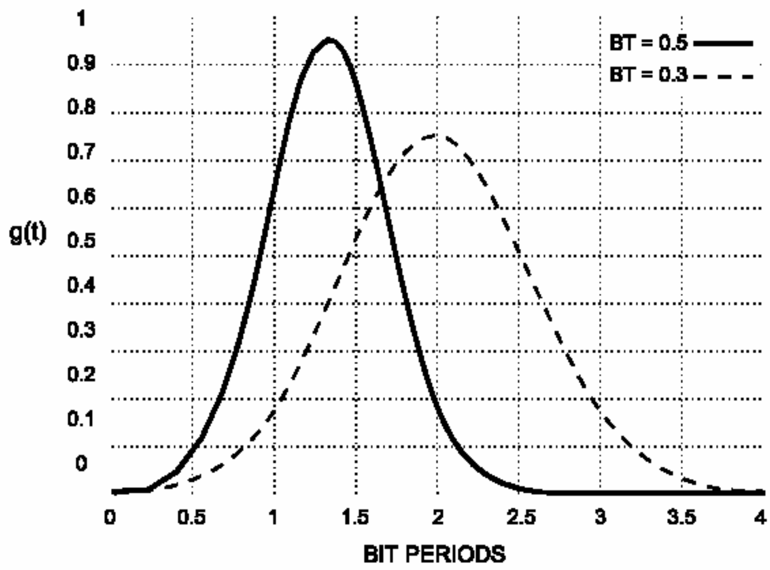

Figure 15: Gaussian filter impulse response for BT=0.3 and BT=0.5.

BT is related to the filter's -3 dB bandwidth and data rate by the following relation:

$$BT = f_{-3\ dB} / BIT\_RATE$$

Hence, for a data rate of 9600 bit/s and a BT of 0.3, the filter's -3 dB cut-off frequency is 2880 Hz.

Referring to Figure 15, notice that a bit is spread over approximately 3 bit periods for BT=0.3 and two bit periods for BT=0.5. This gives rise to a phenomenon called inter-symbol interference (ISI). For BT=0.3 adjacent symbols or bits will interfere with each other more than for BT=0.5. GMSK with BT=∞ is equivalent to MSK. In other words, MSK does not intentionally introduce ISI. Greater ISI allows the spectrum to be more compact, making demodulation more difficult. Hence, spectral compactness is the primary trade-off in going from MSK to Gaussian pre-modulation filtered MSK.

Figure 16 displays the normalised spectral densities for MSK and GMSK. Notice the reduced sidelobe energy for GMSK. Ultimately, this means that channel spacing can be tighter for GMSK when compared to MSK for the same adjacent channel interference.

The "multi-carrier" GMSK system used by ASCOM can be considered to be a broadband OFDM system. The ASCOM PLC system is operating in the frequency range of 1.6 to 30 MHz. To achieve the highest throughput the carriers are managed dynamically and operated simultaneously. The carrier frequencies have been especially chosen to avoid interference from and to important radio and broadcast services.

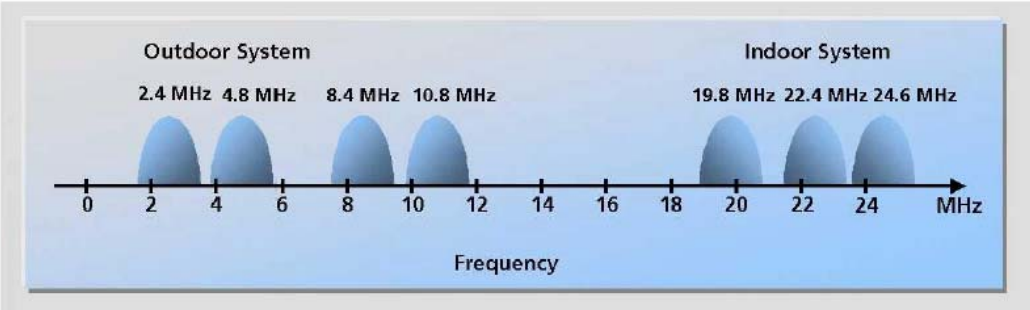

Figure 16: Frequency Allocation in GMSK system from ASCOM.

The choice of the carrier frequencies is based on extensive measurements and frequency planning within the short wave radio band and is in line with the work in progress in CENELEC and with NB30 (Nutzungsbestimmung 30) of the German regulator. Additionally the system satisfies the important European standard CISPR 55022. Each ASCOM PLC system is simultaneously operating on three carriers. Each proving a user data between 750 and 1500 kbits/sec, resulting in a capacity of 2,25 to 4,5 Mbit/s for each PLC system (indoor as well as outdoor).

3.5 DMT (Discrete Multitone Modulation)

With the Discrete Multitone Modulation, the transmit and receive bands are split up into many subchannels, or tones. Each subchannel contains a carrier modulated with data. The number of subchannels and their frequency spacing can be varied. The upstream and downstream spectra occupy different bands, either as individual subchannels or as groups of subchannels for each direction. The location of the upstream above or below the downstream spectra is flexible, so it is possible to optimise the performance depending on the crosstalk and noise environment.

There are many advantages to using DMT modulation. Firstly, because the frequency band is partitioned into discrete subchannels, the transmitter can avoid the noisy ones and maximise the bit rate using the best subchannels. Suppressing energy in those subchannels that overlap the radio bands can reduce the complexity of the notch filters significantly.

Both symmetric and a wide variety of asymmetric configurations can be supported by changing the ratio of upstream to downstream subchannels dynamically. There is an advantage in using the same symmetry for all the modems that share a cable binder. Not only does this greatly simplify the crosstalk environment, it can also reduce its impact significantly, which can then lead to either an extended reach or a higher data rate.

4 PLC Product Suppliers

Company	Market Type	Access	In-house	Chip Source	Modulation	Data Rate (Mbps)	Trial Sites
DS2	Chips	X	X	DS2	OFDM	45	1
Enikia	Chips	X	X	Enikia	OFDM	20	2
Intellon	Chips		X	Intellon	OFDM	14	1
Itran	Chips	X	X	Itran	DSSS	2.5	?
Inari	Products		X	Inari	DMT	2	?
NAMS	Solutions	X	X	Itran	DSSS	2.5	1
M@in.net	Solutions	X	X	Itran	DSSS	2.5	10
ASCOM	Solutions	X	X	ASCOM	GMSK	4.5	15

Table 1: Main PLC component suppliers.

The main PLC technology providers (those that have known customers and whose technology has been proven in the field) are:

- **DS2**: 1280-carriers OFDM modulation technology can provide up to 45 Mbps in a 10 MHz range. DS2 targets both access and home networking markets. It supports both LV and MV transmission medium. Its frequency allocation is compatible with European standards. Several equipment manufacturers use technology from DS2: Ilevo (Sweden), EasyPlug (France), Sumitomo (Japan), Toyocom (Japan), and Ambient (US). DS2 technology has been evaluated in trial tests by different utilities: EDP, Endesa, ENEL, Unión Fenosa, Iberdrola, etc.

- **Intellon**: The HomePlug standard is based on their technology (84-carriers OFDM, 14 MHz theoretical data rate, 6-8 Mbps actual rate). Intellon is exclusively focused on the home networking market (its technology does not support repeaters, which precludes it from being used in long-distance scenarios). Its inefficient frequency allocation (from 4 to 20 MHz) is incompatible with European standard regarding access and in-house coexistence. Three companies (Cogency, Conexant and Valence) have competing chips that are also HomePlug compliant, while others (Enikia and Telewise) will soon deliver compatible chips.

- **Itran**: 2.5 Mbps DS-CDMA modulation technology. It is not compatible with European standard regarding coexistence between access and in-house. Its main customer is the Israeli Company Main.net. It supports both LV and MV transmission medium. It also supplies technology to NAMS. Itran technology has been evaluated in trial tests by different utilities: EDF, Linz Strom, MW, NUON, ENEL, Unión Fenosa, Vattenfall, etc.

- **ASCOM**: It is based on a 4.5 Mbps GSMK modulation technology. Ascom develops both the core technology and the equipment. Frequency allocation is compatible with European standards. It supports only LV transmission medium. ASCOM technology has been evaluated in trial tests by different utilities: EDF, EEF, EnBW, Endesa, ENEL, TIWAG, Iberdrola, etc.

5 PLC System Architecture

A typical Power Line Communication System (PLC) is a full duplex point to multipoint network and consists of the following three components:

- Head End (HE): acts as a router and is placed at the transformer.
- Customer Premise Equipment (CPE): is the customer's modem.
- Home Gateway (HG): is used as a repeater where the signal is low or as a router.

Other devices could be using PLC, like set-top-boxes, which also may incorporate other access technologies, like satellite links.

The diagram shown in Figure 17 is a typical PLC network topology.

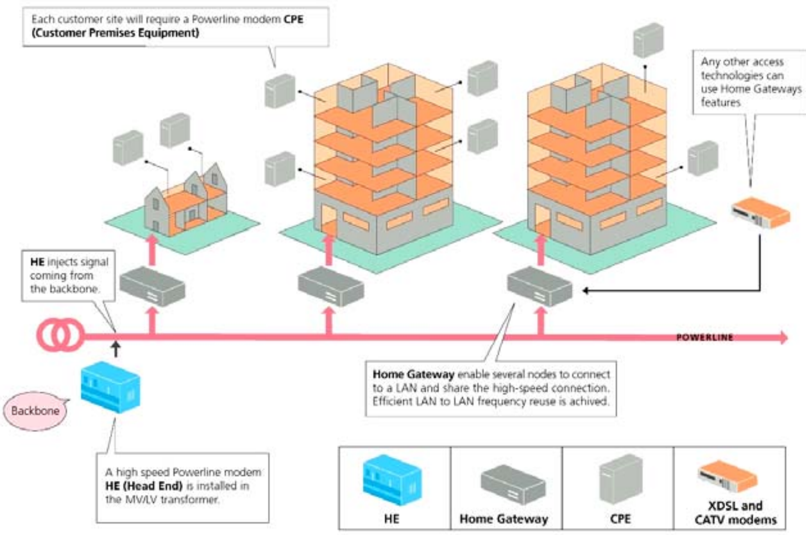

Figure 17: PLC Architecture.

5.1 Head End (HE)

The HE is usually located at the MV/LV (medium voltage / low voltage) transformer. Using frequency and spatial diversity, several HEs can be located on a network. The HE is a high-speed digital modem usually owned by the utility company. It consists of a router that contains a Power line modem card based PLC technology. The HE is placed at the transformer and communicates with several Home Gateways and/or CPEs. The HE is the communications master on the network providing high bandwidth access to several nodes (at least 200 nodes).

The HE is connected at the transformer station to the bus bars as shown in Figure 18.

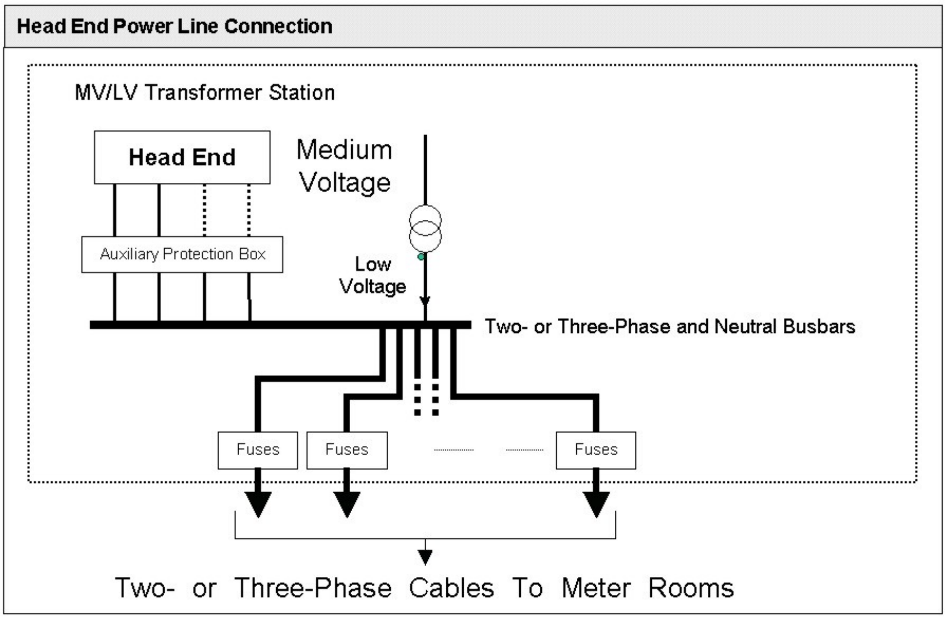

Figure 18: Head End Connection Schema.

5.2 Customer Premises Equipment (CPE)

The CPE is usually owned by the user and is located at the user's electricity plug or outlet. Upstream data is transmitted from the CPEs to the HE or to the Home Gateway. The CPE is connected to the user's computer through an Ethernet connection directly or through an Ethernet hub. A telephone gateway (Tel Gateway) may also be used to enable an analog phone connection through the power line.

This modem can be in a decoder type box or as a PC card installed in the user's computer normally located at the user's electrical socket.

The data is transmitted from the CPE to the HE. The CPE is a slave on the network and must be allocated access to the network by the HE. The HE will also assign unique time and frequency slots on the channel to the CPEs to allow them to transmit simultaneously.

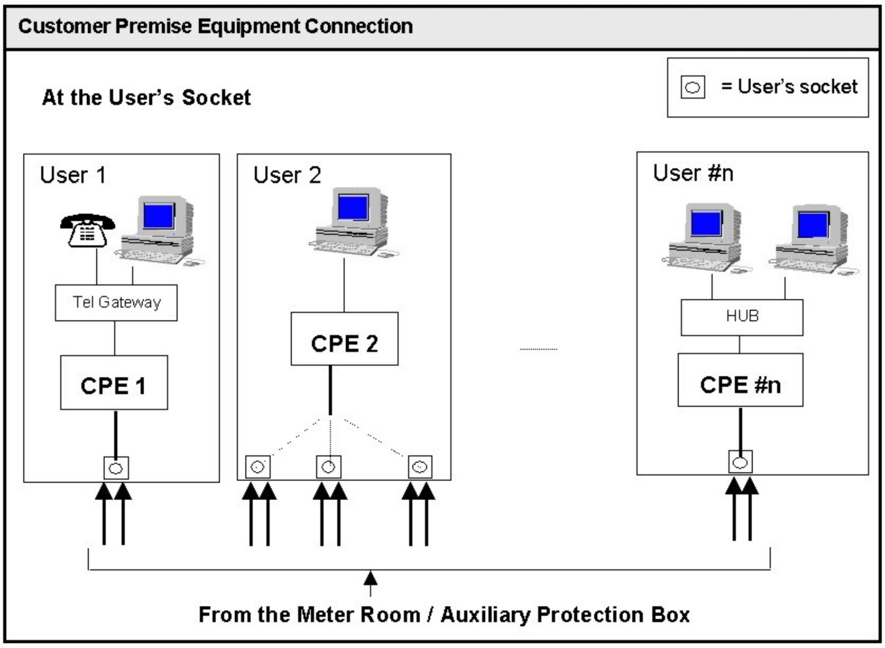

Figure 19: CPE Connection.

5.3 Home Gateway (HG)

A Home Gateway is a combination of a CPE and HE. It can be used both as a repeater to boost the transmitted signal over long distances or where there is a large amount of attenuation affecting the signal, and as a router to implement an in-home LAN. If a Home Gateway is required, it is normally located at the electricity point of entry to a building such as a meter room or protection box. This fact makes it excellent as an access distribution system, where cable operators have a cost-effective solution to distribute their signal without any additional infrastructure.

Home Gateways could also serve as access points to the network for corporate LANs, including interfaces for other kinds of technologies (WLANs, Ethernet, etc.).

A Home Gateway can be used to expand coverage or improve bandwidth in difficult branches of the network.

6 PLC Related Standards in Europe

In Europe standards may achieve the weight of law:

- as a National standard for individual countries via adoption by that country's National Standards Organisation,
- as a Harmonised Standard for the entire EU via acceptance into the Official Journal (OJ) of the European Commission (EC) and subsequently enacted into National law.

Harmonised Standards take precedence, meaning that National Standards should not be produced (standstill) if a Harmonised Standard is in progress and conflicting National Standards must be withdrawn.

Radio spectrum and its protection still remain the concern of individual nations (e.g., Radio Agency in the UK, RegTP in Germany, Agence Nationale des Fréquences in France, Cuadro Nacional de Atribución de Frecuencias CNAF in Spain, etc.).

6.1 Standardisation Issues

The main regulatory issue for PLC is its risk of interfering with other users of the radio spectrum. Earlier systems as the NOR.WEB technology emitted a high level of radio noise in a bandwidth starting at 1 MHz and reaching up to 30 MHz. This caused conflicts with the British government's Radio Agency, which formulated a 0 dBV/m threshold (MPT 1570 limits). This made impossible to use PLC in the UK and certainly contributed to the withdrawal of NOR.WEB from the business.

Few Member States have a regulatory tool which both protects existing frequency users while giving new broadband technologies a spectrum in which to operate and a legal basis for releasing the necessary investments. In order to illustrate the issues involved in the regulatory situation, the German experience is a good example. The German regulator provides PLC system operators with a threshold that he considers sufficiently high to protect the rights of existing frequency users and at the same time sufficiently liberal to allow PLC technologies to successfully develop a product.

The German telecommunication law (TKG) of 1997 explicitly states the right to operate public networks along electrical conductors of any type. It also requests the regulator to draft the necessary regulations in order to facilitate the operation of such services. The German Ministry of Economics (BMWi) and the regulation authority (RegTP) stated an amendment to the frequency regulations titled "Usage Regulation 30 ruling the Plan for Allocating Frequency Areas", also known as NB30.

The allowed emission limit established by NB30 is between 40 dBμV/m and 30 dBμV/m (depending on the frequencies) measured at 3 meters with a peak detector. This regulation is much more restrictive (30 to 40 dB) than the corresponding FCC part 15 in the USA applicable for example to HomePlug (30 dBμV/m at 30 meters with a quasi-peak detector).

Technology providers and operators have requested the national regulators and international frequency coordinating bodies for all unused frequencies between 1 and 30 MHz to be assigned to the use of PLC up to certain transmission powers. However, even if the NB30 is implemented as it stands now, the solution would be to inject less power to stay within the limit. As a result, only a maximum distance of under 300 m could be achieved.

The low peak approach systems (e.g. DS-CDMA) apply complex signal conditioning mechanisms. Each customer station may include a repeater to regenerate the signal.

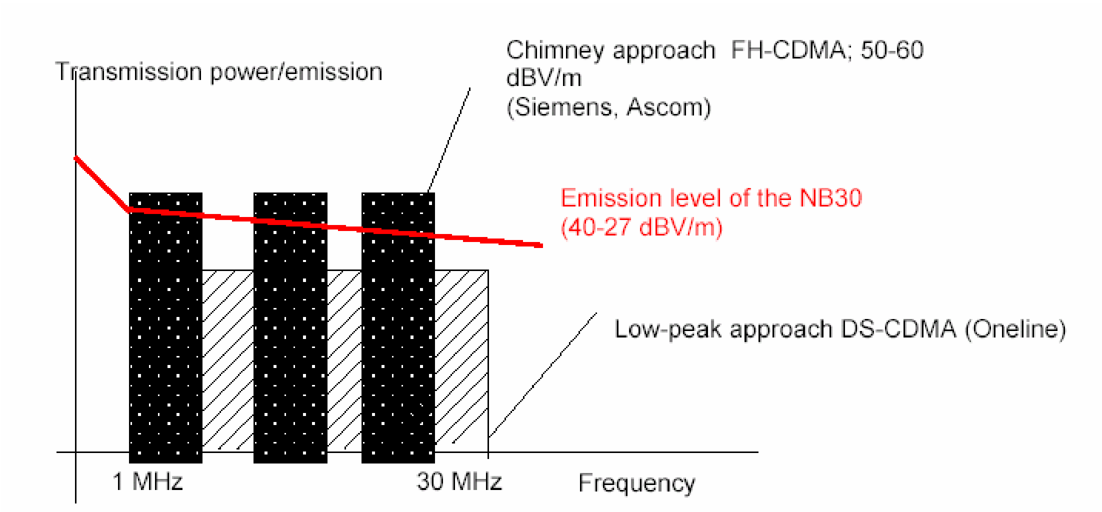

Figure 20: Electromagnetic compatibility according to NB30.

In order for PLC to succeed as a viable alternative for Broadband Communications the regulation bodies and the industry agreed in some start points or basic considerations:

- Broadband communications systems are an important enabler for the information society.
- Competition in the local-loop is required, representing PLC the best alternative for real competition in the local-loop.
- Broadband communication systems should be allowed to perform at the maximum capacity possible without disturbing radio services due to unintentional radiations.
- Field trials are the best way to properly set limits for unintentional radiations.
- All broadband communication systems should have to comply with the same limits (e.g. including ADSL).
- The limits should allow the current deployed systems or appliances (Ethernet, TVs, Halogen lamps, inductive ovens, etc.) to perform without changes.
- Limits should be flat with frequency.
- Limits should be as harmonised as possible worldwide.

Neither ETSI nor CENELEC power line committees tried to tackle the EMC Emission issue, largely due to the lack of consensus among manufacturers about levels needed.

Due to the Mandate 313 (technical harmonised standards for radiated limits for networks in Europe) from the European Union, CENELEC and ETSI founded a Joint Working Group on EMC of Conducted Transmission Networks. The objective is to formulate immunity and emission requirements based on a common approach for CATV, powerline and telecommunication networks (up o 30 MHz). The result of this group are fundamental to many interests, including shortwave broadcasters, defence organisations, amateur radio users, service providers and manufacturers of equipment for Ethernet, xDSL, PLC access and in-home equipment, etc.

6.2 CENELEC

CENELEC, the European Committee for Electrotechnical Standardisation, is a non-profit-making technical organisation set up under Belgian law and composed of the National Electrotechnical Committees of 19 European countries.

The initial CENELEC standard was outlined in EN50065-1 and was set in 1991. The band from 3kHz to 148.5kHz was split into sub bands with each band being allocated to different users.

The focus of CENELEC and the frequencies that were agreed and allocated for Power Line Communications by them have been ideal for the purpose for which they were intended, i.e. telemetry within the power distribution industry. Employing these frequencies for use in a commercial telecommunications network presents physical barriers in terms of achievable bandwidth that renders the prospect of a commercial telecommunications access system on the Power Line platform, at these frequencies, impractical.

As a consequence it was necessary to design higher frequency bands to support a viable telecommunications network. Based on all available information from current developers of PLC modem technology, CENELEC designated frequency bands between 1MHz and 30 MHz providing a basis for a viable access solution. This frequency range is chosen because below 1 MHz, effective separation of the power frequencies is impractical because of the requirement for physically large components. Above 30 MHz the signal attenuation on a power distribution system is considered to be too high. The selection by CENELEC of a 1-30 MHz band would clearly allow a basis for viable alternative local access.

The mission of the SC205A committee (Mains communicating systems) of CENELEC is to prepare harmonised standards for communication systems using low voltage electricity supply lines or the wiring of buildings as a transmission medium and using frequencies above 3 kHz and up to 30 MHz. This includes the allocation of frequency bands for signal transmissions on the mains. Table 2 lists the available standards and the standards in-progress concerning the 1,6 MHz to 30 MHz range.

Reference	Title
EN 50065-1:2001	Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148,5 kHz—Part 1:General requirements, frequency bands and electromagnetic disturbances.
EN 50065-4-1:2001	Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148,5 kHz—Part 4-1:Low voltage decoupling filters-Generic specification.
EN 50065-4-2:2001	Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148,5 kHz—Part 4-2:Low voltage decoupling filters-Safety requirements.
EN 50065-7:2001	Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148,5 kHz—Part 7:Equipment impedance.
R205-006:1996	Mains communication systems-Protocol and data integrity and interfaces.
R210-008:2002	Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148,5 kHz—Part 2-3:Immunity requirements for mains communications equipment and systems operating in the range of frequencies 3 kHz to 95 kHz and intended for use by electricity suppliers and distributors-Recommendations on necessary concepts to model behavioural semantics.
prEN 50412-1:200X	Immunity requirements for power line communication apparatus and systems used in low-voltage installations in the frequency range 1,6 MHz to 30 MHz—Part 1: Residential, commercial and industrial environment.
prEN 50065-4-7:2004	Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148,5 kHz and from 1,6 MHz to 30 MHz – Part 4-7: Portable low voltage decouplig filters – Safety requirements.
EN 50065-4-2:2001/prA2	Signalling on low-voltage electrical installations in the frequency range 3 kHz to 30 MHz—Part 4-2:Low voltage decoupling filters-Safety requirements.
prEN 50412-Z:200X	Signalling on low-voltage electrical installations in the frequency range 1,6 MHz to 30 MHz – Part Z: Low voltage decoupling filters – Generic specification.
CLC/prTR 50412:200X	Guide to standards intended for power line communication in low voltage installations, in the frequency range 1,6 MHz to 30 MHz – Introductory document.

Table 2: CNELEC Approved and In-Progress Standards.

6.3 ETSI-PLT

ETSI produces a wide range of standards independently from telecommunications authorities, including Harmonised Standards.

ETSI-PLT (Power Line Telecommunications) aims at approving the necessary standards and specifications to cover the provision of voice and data services over the mains power transmission and distribution network and/or in-building electricity wiring. The standards will be developed in sufficient detail to allow interoperability between equipment from different manufacturers and co-existence of multiple power line systems within the same environment.

ETSI PLT has published three standards (Table 3):

Reference	Title
TS 101867	Coexistence of Access and In-House Powerline systems
TS 101896	Reference Network Architecture Model
TR 102049	QoS for in-home

Table 3: ETSI PLT Standards.

The ETSI has another Harmonised Standard EN 300 386 titled “Emission and Immunity Requirements from equipment used in telecommunication networks” that can be used as a reference for a PLT access standard and for the EU Commission Mandate M313.

6.4 IEC (CISPR)

The IEC (International Electrotechnical Commission) by the CISPR (International Special Committee on Radio Interference) is amending the EN 55022 (CISPR 22) to take into account PLC (in-house and access equipment). This is an emission standard used for most Telecommunication equipment (Information Technology Equipment). CISPR agrees in 2001 to incorporate PLT industry work into Task Force xDSL. This joined Task Force xDSL/PLT decided to:

- Adopt the same Electrical and Magnetic Field limits for all technologies.
- Use the same common mode limits for all technologies.
- Apply Telecommunications port limits to PLT modems in transmit mode.
- Base the LCL (Longitudinal Conversion Loss) measurements for PLT on field measurements.

7 Trial and Commercial PLC

Broadband PLC services such as high speed Internet are commercially available in several European countries. In Table 4 the main service providers in commercial and trial status are shown.

Country	Utility	Services	Scope	Technology
Commercial				
Germany	MW	Access PLC. Internet services (residential) (under Piper-Net brand) www.piper-net.de	2.200 users in Manheim	Mainnet
	EnBW	Access & In-home PLC. Internet services (hotels, schools)	700 users in Ellwagen	ASCOM
	RWE	Access & In-home PLC. Internet services		ASCOM
Spain	Endesa	Access PLC. Internet & voice services (agreement with Telecommunications Company AUNA)	2.200 users in Zaragoza	DS2-ASCOM
	Iberdrola	Access PLC. Internet & voice services (agreement with Telecommunications Company Neo-Sky)	200 users in Madrid	NAMS-DS2-ASCOM
Austria	Linz Strom AG	Access & In-home PLC. Internet & voice services (under Speed-Web brand) www.linzag.net	800 users in Linz	Mainnet
	Tiwag	Access PLC. Internet services (hotels, residential, schools)	250 users in Tirol	ASCOM
Sweden	Vattenfall	Access PLC. Internet services (residential) (under ENKom brand) www.enkom.nu	500 users in Gotland Island	Mainnet
Switzerland	EFF	Access PLC. Internet services (agreement with Sunrise Internet Service Provider)	1.000 users in Geneve	ASCOM
Trial				
Spain	Union Fenosa	Access PLC & In-home PLC. Internet & voice services.	50 users in Madrid and Guadalajara	Mainnet-DS2
Portugal	EDP	Access PLC. Internet & voice services (agreement with Telecommunications Company ONI)	300 users in Lisbon	DS2-ASCOM
Italy	ENEL	Access PLC. Internet & voice services	3000 users in Grosetto (Tuscany)	DS2-ASCOM-Mainnet
Netherlands	Nuon	Access PLC. Internet services (under Digitsroom brand)	250 users in Arnhem	Mainnet

Table 4: Commercial & Trial Experiences.

7.1 PLC in Spain

In October 2003, the Spanish Telecommunication Market Commission (CMT) granted Endesa, Iberdrola and Unión Fenosa, the Spain's three main electric companies, licenses to offer voice and data services over their grids. Using PLC technology, these companies offer a serious alternative for broadband services to their customers in Spain.

For the moment, the Spanish electric companies have chosen the strategy of becoming PLC providers for other telecommunications operators, without entering directly into public service. These power companies provide the last mile access infrastructure and offer commercial services through the telecommunications operators in which they are stockholders. Endesa and Unión Fenosa are both negotiating collaboration with Auna (Spain second telecom operator) to commercially launch voice and data services over the electrical grid and Iberdrola has already launched broadband Internet services through its telecommunication operator Neo-Sky.

In the case of Endesa, Spain´s largest electrical company, voice and broadband access is being offered in Zaragoza through company affiliate "Endesa Net Factory" and Auna. The Endesa commercial offering comes of a massive successful pilot in the city of Zaragoza. PLC commercial services in Zaragoza will take advantage of the 20.000 home network that was rolled out for the pilot. A second phase was planned for January 2004 to launch commercial PLC services in Barcelona.

Union Fenosa has also conducted pilots in Madrid and some outlying suburbs.

Iberdrola, Spain's second electric company, is offering the commercial service to 30.000 inhabitants in two densely populated districts in the north of Madrid, and it will be extended throughout the city according to demand.

As a conclusion, PLC is the third broadband access system available in Spain, after ADSL and cable. The news of its commercial launch has created great expectations because of its attractive pricing and speed, as compared with current Spanish ADSL offers. For the moment, rollouts are limited to geographical areas covered under initial pilot test areas. Depending upon take-up of the offer, PLC will gradually be offered throughout the major cities in Spain.

Perhaps for Spain and other countries, the most important long-term aspect of PLC is not better pricing and higher symmetrical transmission speeds, but the possibility for broadband services to be offered in areas where ADSL and cable services are not offered.

7.1.1 Endesa Massive Technology Trial

The Massive Technology Trial, hosted in Zaragoza (Spain), allowed Endesa to identify the main issues related to PLC technology and its deployment. The main objectives were:

- Analyse the technical viability of PLC (testing different topologies of the electricity infrastructure and evaluating the compliance with EMC directives),
- Design a telecommunications network architecture providing voice-over-PLC services or Internet broadband access, to measure the degree of user satisfaction and,

- Validate some assumptions made in the planned business plan (PLC deployment costs and speed of the PLC deployment)

Some characteristics of the trial are summarised next:
- Date of launch: September 2001
- Duration of the trial: 12-18 months
- Dimension: 2.100 final users (individuals and professionals) in Zaragoza
- A specific license was obtained in order to conduct the trial in February 2002
- The services offered are Voice-over-PLC (VoPLC) and high speed Internet access (up to 20 Mbps)
- The trial deployed technologies which had already been proven during the previous trials of Endesa in Sevilla (DS2) and Barcelona (ASCOM)
- In this trial has been evaluated the data transmission over the Medium Voltage network by using DS2 technology
- Existing telecommunications infrastructure has been used where available

The PLC trial network was rolled out selectively and complementary to the existing fiber network from other operators. A PLC telecommunication network covering 20.000 homes was implemented in five months, being the roll out selective at area and building levels (complementary with existing infrastructure). Consequences of the innovative application of Medium Voltage PLC are the decreasing investment and the speeding up roll out. The implantation has been innocuous with more than 600 interventions in substations and meter rooms without any interruption of the electrical service.

300 buildings and 2.103 users were deployed and placed in service in five months (seven months less than using Hybrid Fiber Coaxial HFC technology), connecting 140 low voltage transformers (56 with optical fibre and 84 with PLC medium voltage). The use of fibre rings and medium voltage rings has increased the speed and reduced the cost of deployment.

In this trial different concentration levels of users per LV transformer and meter room were tested in order to evaluate the influence in QoS (Quality of Service).

The investment per user without including the CPE (Customer Premises equipment) is a third of the cost for the HFC technology.

The analysis of traffic in the PLC network is resumed in the Table 5:

Users	**Download Rate (daily)**
10%	1 Gb
20%	100 Mb
48%	5 Mb

Table 5: Data Traffic in PLC.

A remarkable point is that the emission levels measured with the PLC technology used in these trials are similar or even smaller that those measured with the corresponding ADSL technology. In Spain the emission levels (PLC or ADSL technologies) are not regulated by now. The regulatory organism in Spain (MCyT Ministerio de Ciencia y Tecnología) requires solving the possible incidents as they surge.

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Part II – MICROGRIDS Architecture

1 Introduction

The main objective of WPF was to provide the communications platform necessary for supporting the MICROGRIDS control architecture, which requires interaction between a Micro Grid Central Controller (MGCC) and local Micro Source Controllers (MC) and Load Controllers (LC) as well as communications with a Distributed Management System (DMS).

Specific objectives of WPF included the analysis of system requirements (both general as well as application related), the specification of the communications architecture (with selection of protocols and interfaces) capable of fulfilling these requirements, the choice of an adequate platform to support the execution of the MICROGRIDS control applications and finally the evaluation of the architecture, mainly from the point of view of performance and scalability.

One particular topic relevant for the specification of the architecture is the physical communications infrastructure. At the start of the project (and still today), Power Line Communications (PLC) was considered as one possible candidate, among the available access network (last mile) technologies. Therefore, it had been proposed, as task F2, to make a full characterization of the power grid as a communications infrastructure. Due to the particular nature of this topic and the fact that it can be treated in an autonomous way, it was decided to present it separately, in Part I of this deliverable.

The analysis of requirements and decisions taken in conjunction with other work packages lead to the proposal of using an agents' platform to support the control applications envisaged by the project. The development of the agents that populate the platform is not the responsibility of WPF.

Therefore, the next chapters of Part II of this deliverable are devoted to the identification of the MICROGRIDS communications requirements, the proposed architecture (that includes a distributed agents' platform) and finally its evaluation (mainly the message transport system).

2 Analysis of Requirements

System requirements encompass all layers of a complete communications protocol stack. However, for simplicity, three levels of abstraction were considered in the analysis: application related functions, intermediate (transport and network layer) functions and the physical communications infrastructure (subnetwork).

One general requirement calls for the use, whenever possible, of standard protocols and open technologies and tools; this means adopting a modular, layered architecture. This allows designing and developing modular solutions using off-the-shelf, low cost, widely available and fully supported hardware and software components, as well as scalability for future expansion and enhancements.

The choice of a suitable protocol stack must take into account the nature of the MICROGRIDS control architecture. This can be seen (at least in the present system) as a master/slave architecture, with one master or primary station, the Micro Grid Central Controller (MGCC) and a number of slave or secondary stations – the local micro source controllers (MC) and load controllers (LC).

In traditional master/slave control applications, stations normally share a communications channel, using either a centralised or a distributed multi-access protocol, like in multidrop and shared LAN topologies, respectively. Communications usually take place between the master station and each slave (point-to-point logical channel), although multicast or broadcast from the master to the set or a subset of the slave stations could be advantageous in some cases.

To fulfil these basic requirements, a flat network solution would suffice, that is, the control application could run directly over a data link layer protocol. However, many advantages can be gained by using standard network and transport protocols, which, at present, means using the TCP/IP family:

- independence of subnetwork technology;
- possibility of sharing a physical subnetwork with other services and applications;
- global or local addressing schemes at network level (logical, not physical);
- integration within a wider IP network (internetworking support);
- provision of standard transport services (TCP or UDP);
- exploitation of TCP reliability mechanism;
- use of existing or new services that run on top of TCP or UDP and that may benefit from the widespread use of application protocols like HTTP.

Thus, using TCP/IP as the intermediate layers in the MICROGRIDS architecture provides extra functionality, flexibility and scalability, especially in what concerns future evolutions, such as the exploitation of more complex scenarios (for example, multiple micro-grids) or the use of a variety of physical communication services (depending on the actual offer by network operators).

In what concerns the physical infrastructure, the adoption of IP for the internetwork layer means that any subnetwork technology can be adopted and the choice depends on a number of factors, especially availability, ease of deployment and cost.

At present, a number of access solutions are available, such as ISDN, xDSL, WiMax, cable, Wi-Fi (IEEE 802.11), Ethernet in the First Mile (EFM), etc. In this scenario, PLC is emerging as a new last mile access technology for broadband Internet access.

For supporting the MICROGRIDS control architecture, the exploitation of a “dedicated” PLC based solution does not seem reasonable, since the control traffic alone would hardly justify the high investment and maintenance costs of such an infrastructure. Therefore, this access solution should be considered in the broader context of the commercial exploitation of PLC based Internet broadband access services.

The possibility of adopting different access technologies, depending on availability and cost of services offered by operators, is therefore an advantage of the proposed architecture. This diversity avoids the dependency on a single technology, provides more freedom and flexibility to the system designer and allows the provision of back-up solutions.

According to the previous analysis, it is proposed to support the MICROGRIDS control architecture without any specific dependence on the access technology, since a number of alternatives support the basic requirements.

Analysing in more detail the MICROGRIDS architecture from the application point of view, two broad types of requirements were derived.

One is related with the nature of the application and includes the analysis of communication patterns and temporal behaviour (trigger events and their frequency, actions to be performed, traffic volume, etc.) and identification of data types. The analysis of these requirements is necessary to specify in detail the application protocol (procedures, messages and timing) and to derive performance related figures (throughput, response time, etc.).

The other is related with the basic services required from the underlying layers, especially in what concerns establishment and management of communication sessions as well as service availability, reliability and security, and therefore is strongly related with the previous analysis on the intermediate layers.

The communication requirements were analysed from the perspective of TB3 (Agents for secondary control) and TC4 (Demand Side Management) and were included in a report produced by LABEIN. The report follows the standard practice for communication systems design, covering data transfer triggers, data types, mapping for TB3 and TC4 parameters, as well as data requirements for security, performance and throughput analysis.

It was possible to conclude that these requirements have not a serious impact on the communications infrastructure, taking into account the level of service provided by the existing technologies, as far as connectivity, throughput and response time.

Since the adoption of the IP family of protocols was driven by reasons mentioned above, the most critical architectural choice was related with the middleware layers that provide the environment for running the applications.

The decision was finally to use an agents' platform and therefore, from the point of view of WPF, two issues remained to be dealt with: first the integration of the platform into the overall architecture and second the performance evaluation of the whole system.

The adoption of a TCP/IP based protocol stack and the independence of the underlying communications infrastructure brought up two important advantages: the possibility of developing the software agents and running the platform in a LAN environment, as well as carrying out the performance and scalability tests by populating the platform with an arbitrary number of agents that communicate using the real message transport protocols supported by the agents platform.

3 Communications architecture

The analysis of requirements allowed deriving two important conclusions. In the first place the advantages of basing the MICROGRIDS architecture in the TCP/IP protocol stack and in the second place the possibility of selecting among various access network technologies, since this choice is not critical from the applications point of view.

This led naturally to concentrating the attention into the architectural environment for running the MICROGRIDS applications. The main issue for WPF, from the architectural point of view, was the integration of the agents' platform with the lower protocol layers.

The decision taken by the project was to use an agents' platform based on the *Java Agent DEvelopment Framework* (JADE).

JADE is a middleware software environment for the development of applications based on agents, according to the specifications of the *Foundation for Intelligent Physical Agents* (FIPA); it provides both a development framework and an agents' platform. Its main objective is to simplify and ease the development of multi-agent systems and to ensure interoperability among different multi-agent systems, by means of a broad set of services and system agents that allow communication between agents according to FIPA specifications. JADE is open source and the current version, used in the present work, is JADE 3.3, which has been available since March 2005.

The FIPA reference model for agent platforms is shown in Figure 1. A brief description of its main components is given next.

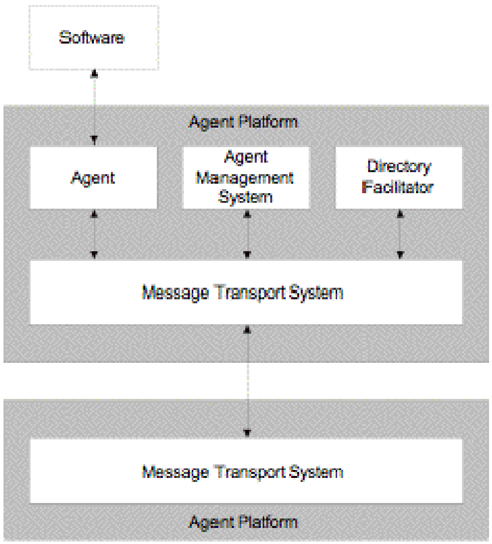

Figure 1: FIPA Reference model.

The *Agent* executes a number of tasks according to the objectives of an application; it runs inside the platform, communicates with other agents by means of messages and interacts with the application (*software*).

An *Agent Management System* (AMS) supervises access to and use of the agent platform and supports the registration and look-up of agents (*white-pages service*). It manages the agent life cycle, contains a directory of *Agent Identifiers* (AID) and establishes the logical model for creation, registration, communication, migration and termination of agents.

A *Directory Facilitator* (DF) provides registration and look-up of services provided by agents (*yellow-pages service*). A platform may contain more than one DF.

A *Message Transport System* (MTS), also called *Agent Communication Channel* (ACC), provides the message transport service; all agents in the same or in different platforms use the ACC to communicate. Different protocols may be used for the communication between JADE platforms, namely *HyperText Transfer Protocol* (HTTP) and the *Internet Inter-ORB Protocol* (IIOP).

IIOP is a protocol that allows the communications between distributed programmes, possibly written in different languages, over the TCP/IP protocol stack. It is a component of standard CORBA (*Common Object Request Broker Architecture).*

CORBA is a standard architecture developed by the *Object Management Group* (OMG) for designing object oriented distributed applications. Invocation of CORBA objects is independent of the platform and of the (object oriented) programming language. *Object Request Broker* (ORB) is an application that provides mechanisms for the communication between objects in such a transparent way, thus ensuring interoperability of different implementations.

Different IIOP implementations are available in JADE, such as the implementation from Sun (SUN ORB) and the CORBA implementation from ORBACUS. These alternatives will be analysed in the following chapter.

JADE agents are executed in a run-time environment called an *agent container*. Each agent runs on its own thread and agents within a container share resources and services (e.g., thread scheduling and messaging support). It is possible to distribute the platform by different machines that need not share the same operating system. The configuration may be controlled by a remote *Graphical User Interface* (GUI) or at *run time* by mobile agents that migrate from machine to machine.

A distributed JADE platform is composed of several run-time containers launched on one or more hosts on a network. Each host typically executes one *Java Virtual Machine* (JVM), which can host one or more JADE instances. One container runs on one JVM and distribution across different hosts is based on JAVA *Remote Method Invocation* (RMI).

The main container hosts the AMS, the DF and a *Remote Method Invocation Registry*. The latter is a name server that JAVA uses to keep references to other agent containers in the same platform. This allows abstracting the physical separation of hosts or different platforms in the same host.

An example of a JADE platform with multiple containers, running on different machines is shown in Figure 2.

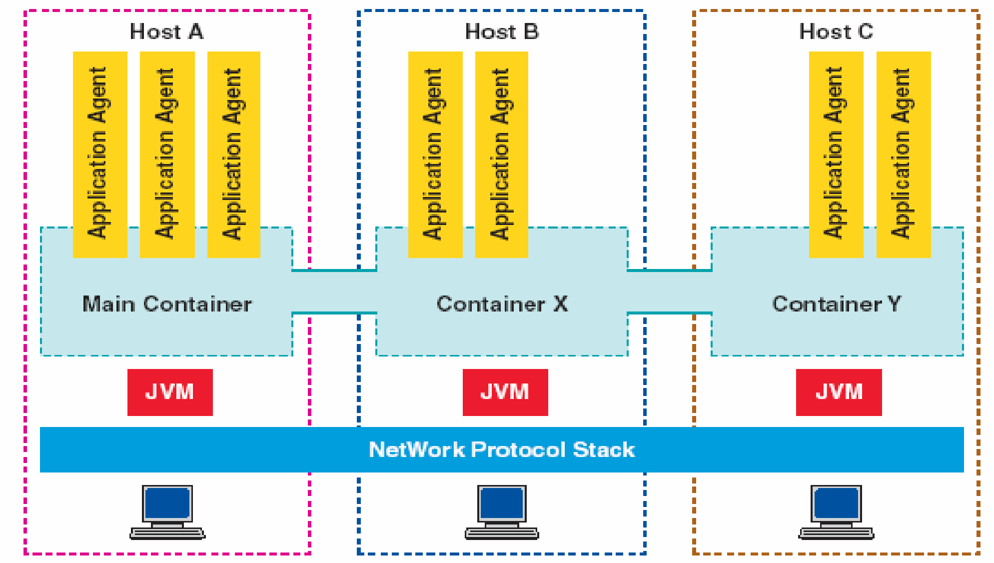

Figure 2**:** JADE platform with multiple containers.

The outline of the MICROGRIDS agents´architecture is presented in Figure 3, where a single platform includes containers residing in different systems – the main container on the Micro-Grid Central Controller and normal containers on Micro-Source and Load Controllers. Each container is populated with the required agents that perform specific tasks

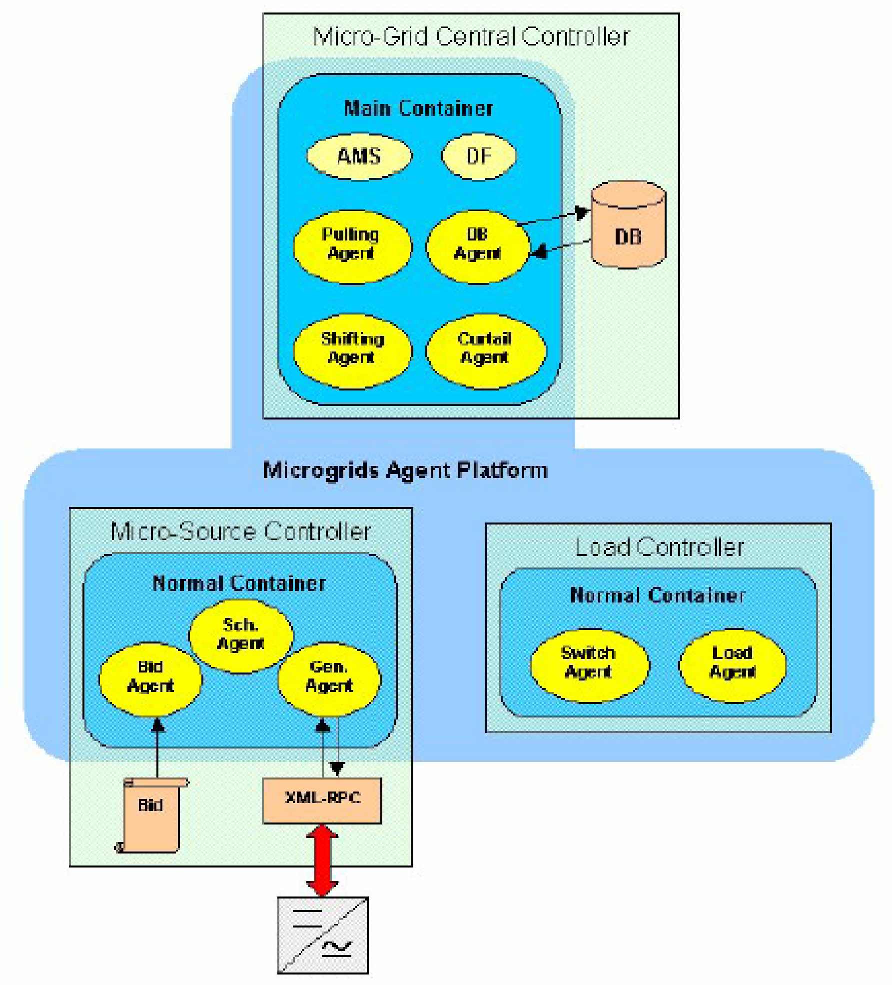

Figure 3: Microgrids Agents' Architecture.

4 Performance simulation and analysis

The most important aspect in the communication between agents is the message exchange, which requires a Message Transfer Protocol (MTP).

In JADE two basic classes support the exchange of messages: *ACLMessage* and *AID*. In a JADE message the sender is always an agent, while one or more agents may act as receiver(s), which requires that all agents must have an Agent Identifier (AID).

The performance evaluation of the JADE platform has been carried out in a number of scenarios and using three message transport protocols identified in the previous chapter: HTTP, Sun IIOP (Sun ORB) and Object CORBA IIOP based on ORBACUS.

4.1 Scenarios

From a communications point of view, a first distinction can be made considering that the agents may reside in the same JADE platform (intra-platform communications) or in different platforms (inter-platform communications). In the first case FIPA does not mandate the use of a specific MTP and therefore the platform developer may define an internal MTP (IMTP). In the second case, interworking between different agent platforms must be guaranteed by MTPs defined by FIPA, such as HTTP, Sun and CORBA IIOP. It is also possible to further distinguish communications between agents in the same or different containers or in the same or different machines.

Considering the possible combinations, four scenarios were considered:

- **Intra-platform communications**
    - Communication between agents residing in the same *container*;
    - Communication between agents residing in different *containers*.
- **Inter-platform communications**
    - Communication between agents located in the same machine;
    - Communication between agents located in in different machines.

For intra-platform communications two IMTPs have been used, with the goal of optimizing message delivery:

- **Event passing** (*call* method) – when sender and receiver agents reside in the same *container*; the message is cloned and a reference is passed to the destination;
- **Java Remote Method Invocation (RMI)** – when sender and receiver agents reside in different *containers*.

In the inter-platform scenario, interaction between agents is carried out by the ACC, which is distributed among all *containers*. Each *container* can be launched with a different MTP and the ACC routes the messages to the intended *container* by means the appropriate MTP.

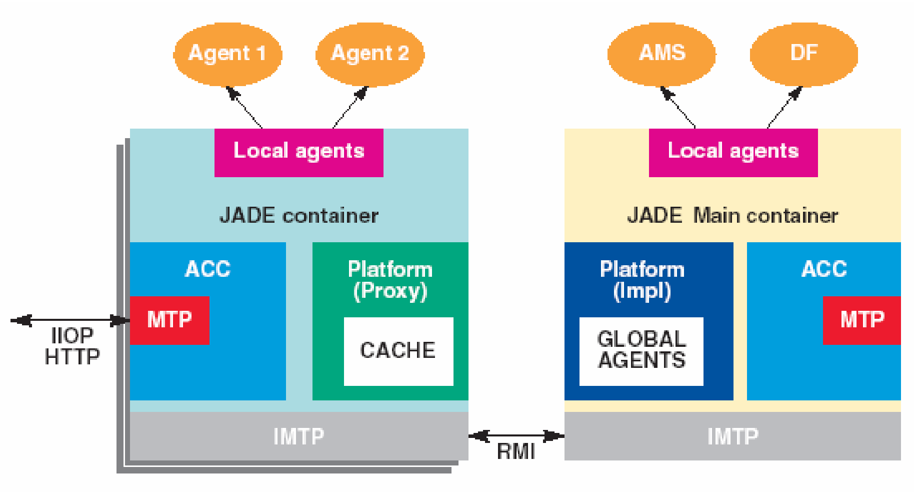

Figure 4: JADE message architecture.

Congestion may occur due to the fact that the *main-container* houses management services. However, this problem is attenuated since the ACC is distributed among all *containers* and MTPs may attach to any *container*. Moreover a *cache* mechanism is implemented in each *container*, so that the physical association of the address names is kept locally, and the *main container* is accessed only when the address information is missing.

4.2 Contract Net Protocol

In the performance tests, the Contract Net Protocol (CNP) was selected. This is a negotiation protocol between agents specified by FIPA. Its importance stems from the fact that it allows automatic negotiation and mutual selection between partners and contractors as well from its simplicity and potentiality. It allows the cooperation and the coordination of actions between agents, based on contracts, to fulfill certain goals.

The protocol involves two types of agents. An *Initiator* acts as a manager and announces tasks to potential partners (*Responders*) that bid for their execution, which is accepted or rejected by the *Initiator*.

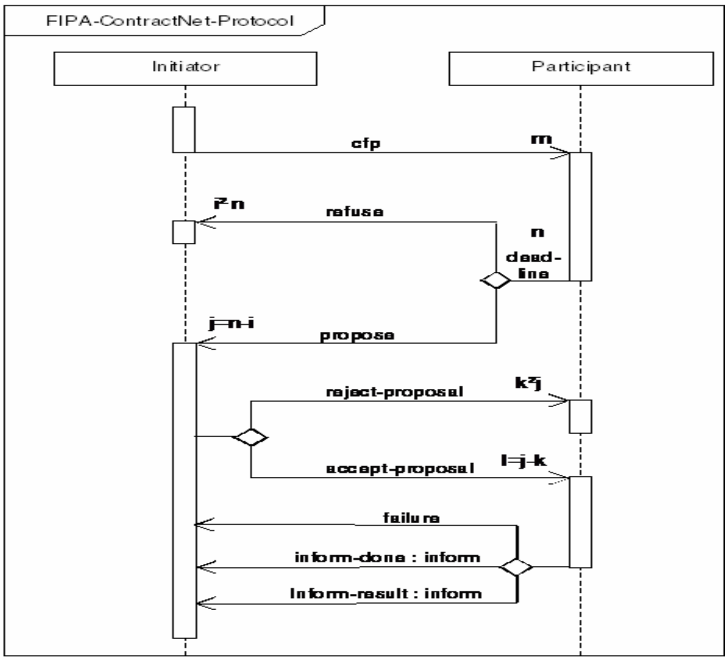

Figure 5: FIPA *Contract Net Protocol.*

4.3 Hardware and Software Configuration

In the tests, two Personal Computers with 100 Mbit/s Ethernet cards were used, with the configuration shown in the Table.

Model/version	Computer A (inesc)	Computer B (mozart)
Processor	Intel(R) Pentium(R) 4 CPU 1500 MHz	Intel(R) Pentium(R) 4 CPU 1700 MHz
Memory	512 MB	256 MB
Network cards	D-Link DFE-530TX PCI Fast Ethernet Adapter (Rev A)	Intel(R) PRO/100 VM Network Connection
Operating System OS)	Microsoft Windows XP Professional	Microsoft Windows XP Professional
OS version	2002 Service Pack 2	2002 Service Pack 2
Java	jdk1.5.0	jdk1.5.0
JADE	3.3	3.3

Table 1: *Hardware* and *software* configuration.

The execution of the Contract Net Protocol requires two types of agents, whose code was developed in JAVA: *ContractNetInitiatorAgent* and *ContractNetResponderAgent*,.

The parameter of interest in this study is the negotiation time as a function of the number of agents. It is possible to derive the average negotiation time as well as the condition where degradation starts to occur, that is, the point (number of agents) where a sharp increase of the overall negotiation time takes place. This provides information about the scalability of the platform.

To have access to the start and end of simulation, two JAVA methods, *public void onStart()* and *public int onEnd()* were used in the *ContractNetInitiatorAgent*. To print the start and end times, a Gregorian calendar was built in JAVA, in order to acquire and format the local time. The following is the example of the *onStart()* method:

```
public void onStart()
       {
            SimpleDateFormat formatter = new
            SimpleDateFormat("yyyy-MM-dd HH:mm:ss.S");
            Calendar calendar = new GregorianCalendar();
            Date trialTime = new Date();
            calendar.setTime(trialTime);
            Date temp = calendar.getTime();
            System.out.println("Inicio simulacao: " +
            formatter.format(temp)+"\n");

            super.onStart();
       }
```

To kill all agents at the end of simulation, *behaviours* were developed in those programs, as exemplified by the *OneShotBehaviour*:

```
addBehaviour(new OneShotBehaviour(myAgent)
       {
       public void action()
              {
                     myAgent.doDelete();
              }
       });
```

For some tests, it was necessary to register and search agents in the DF and indicate search restrictions, as exemplified next:

```
try {
       DFAgentDescription dfd = new DFAgentDescription();
       dfd.setName(getAID());
       ServiceDescription sd = new ServiceDescription();
       sd.setName("responder");
       sd.setType("responder");
       dfd.addServices(sd);
       DFService.register(this, dfd);
  }
  catch (FIPAException fe) {
       fe.printStackTrace();
  }
```

```
DFAgentDescription template = new DFAgentDescription();
ServiceDescription templateSd = new ServiceDescription();
templateSd.setName("responder");
templateSd.setType("responder");
template.addServices(templateSd);

SearchConstraints sc = new SearchConstraints();
sc.setMaxResults(new Long(7000));
sc.setMaxDepth(new Long(2));
       try {
              DFAgentDescription[] results =
              DFService.search(this, template, sc);

              if (results.length > 0) {
              System.out.println("Agent "+getLocalName()+
              "encontrou agentes:");

              for (int i = 0; i < results.length; ++i) {
              DFAgentDescription dfd = results[i];
              AID provider = dfd.getName();
              msg.addReceiver(provider);
                            }
                     }
                     else {
                            System.out.println("Agent "+getLocalName()
                            +" nao encontrou servico responder\n");
                     }
              }
              catch (FIPAException fe) {
                     fe.printStackTrace();
              }
```

A number of JAVA applications were developed to start negotiation and automatically launch the specified number of agents. These applications allow launching agents in the required containers and platforms, according to the test scenario. The following code shows how to launch two *Responder* agents and one *Initiator* agent, respectively.

```
for (n=0;n<2;n++)
       {
       agent_name=new String("ag")+Integer.toString(n);
       dummy = ac.createNewAgent(agent_name,
       "examples.protocols1.ContractNetResponderAgent",new Object[0]);
       dummy.start();

         Thread.sleep(100);
         agent_controllers.add(dummy);
         arguments[n] = agent_name;
         }
```

```
p = new ProfileImpl(null, 1100, null);
AgentContainer another = rt.createAgentContainer(p);
AgentController mobile = another.createNewAgent("Initiator",
"examples.protocols1.ContractNetInitiatorAgent", arguments);
mobile.start();
    }
```

4.4 Experimental tests and results

Experiments were carried out according to the scenarios and configurations previously described, including the choice of alternative MTPs. For each experiment, the number of agents was varied up to a maximum of 7000 and the corresponding simulation time was determined.

4.4.1 Intra-platform communications

For the exchange of messages in the same platform, a single computer was used (computer A). Although FIPA does not specify any MTP for this case, the platform was launched with different MTPs to assess the behaviour of message exchange.

4.4.1.1 Communication within the same container

HTTP

HTTP is the current default MTP used by JADE. The platform address is a URL that contains the platform name in port 7778, for example `http://inesc:7778/acc`. This is the default, but it is possible to redefine the port and name with the options `-port and -name`. The platform is launched with the command

- `java jade.Boot -mtp jade.mtp.http.MessageTransportProtocol -gui`

or, since HTTP is the default MTP, with the equivalent command:

- `java jade.Boot -Xms64M –Xmx512M –gui`

Figure 6 shows how to launch a JADE platform and Figure 7 presents the JADE Graphical User Interface (GUI).

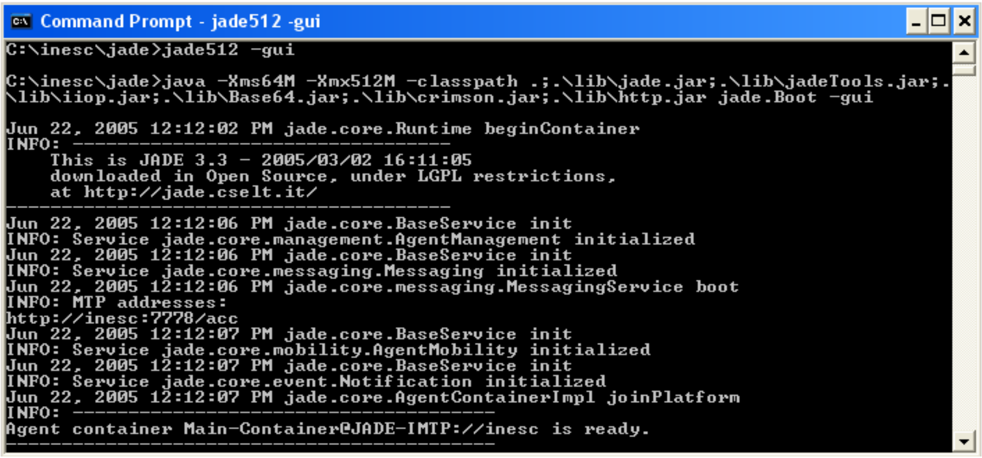

Figure 6: Launch of JADE platform.

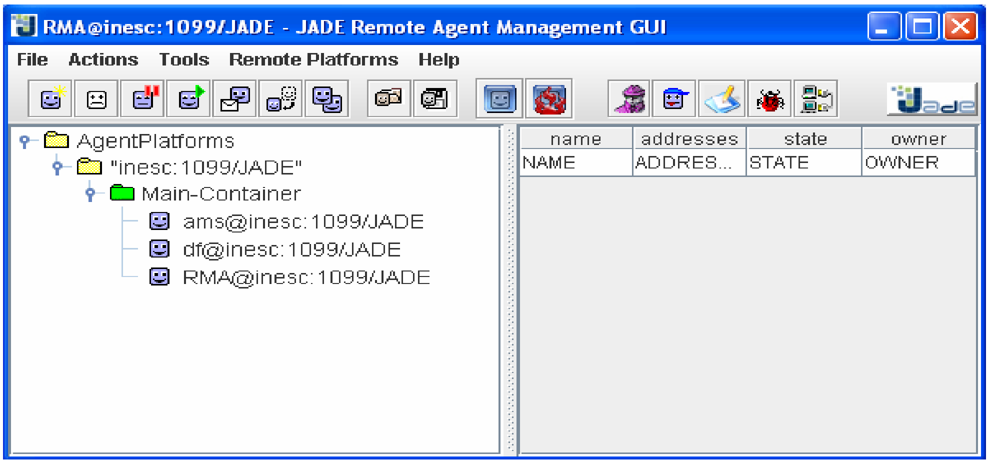

Figure 7: JADE Graphical Interface.

The options `-Xms64M` e `-Xmx512M` are used to define the memory that the Java Virtual Machine (JVM) can use initially and the maximum, respectively. The option `-gui` is used to launch JADE graphical interface.

After launching the platform, the applications that implement the Contract Net Protocol for the specified number of agents are executed (Figure 8), initially with two agents up to a number that lead the system to the onset of congestion:

- ```
  java examples.Simulation0.StartAgents2
                              .StartAgents20
                              .StartAgents200
  ```

  …
  ```

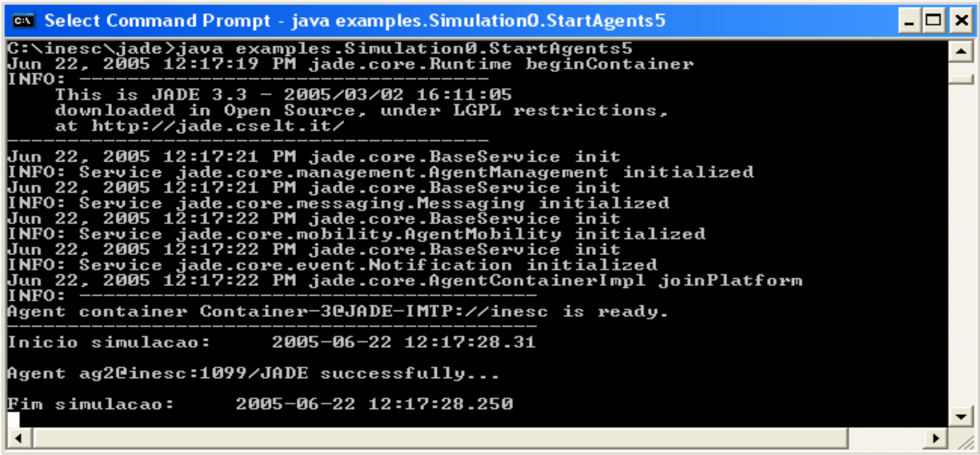

Figure 8: Java application.

Each Java application creates the *Responders* and then launches the *Initiator* (Figure 9).

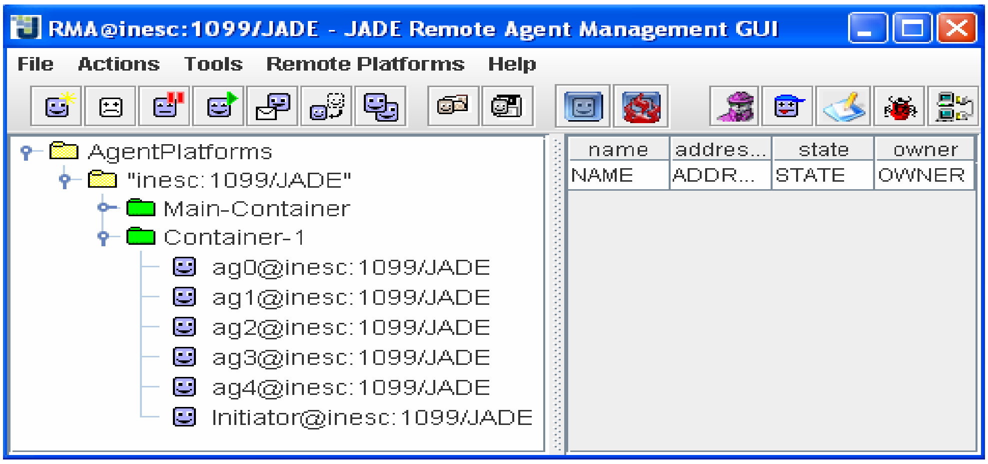

Figure 9: Launching of agents in the same *container*.

The simulation results for this case (intra-platform, single container, HTTP) are presented in Table 2 and Figure 10. Similar tables were obtained for the remaining cases that have been simulated but will not be reproduced; only the corresponding figures will be presented.

Start	End	Time	Nº Agents
2005/06/15 21:49:08.125	2005/06/15 21:49:08.265	00:00.140	2
2005/06/15 21:50:04.734	2005/06/15 21:50:04.906	00:00.172	5
2005/06/15 21:51:56.953	2005/06/15 21:51:57.250	00:00.297	10
2005/06/15 21:52:35.328	2005/06/15 21:52:35.734	00:00.406	20
2005/06/15 21:53:19.000	2005/06/15 21:53:19.781	00:00.781	50
2005/06/15 21:54:13.468	2005/06/15 21:54:15.310	00:01.842	100
2005/06/15 21:56:24.906	2005/06/15 21:56:27.953	00:03.047	200
2005/06/15 21:58:06.500	2005/06/15 21:58:13.531	00:07.031	500
2005/06/15 23:17:32.953	2005/06/15 23:17:45.484	00:12.531	1000
2005/06/16 00:04:19.625	2005/06/16 00:04:36.359	00:16.734	1500
2005/06/15 23:48:05.281	2005/06/15 23:48:24.828	00:19.547	2000
2005/06/16 00:33:59.812	2005/06/16 00:34:20.906	00:21.094	2500
2005/06/16 01:07:03.593	2005/06/16 01:07:30.500	00:26.907	3000
2005/06/16 01:48:39.187	2005/06/16 01:49:10.421	00:31.234	3500
2005/06/16 02:30:08.812	2005/06/16 02:30:42.343	00:33.531	4000
2005/06/16 02:41:56.796	2005/06/16 02:42:32.359	00:35.563	4500
2005/06/16 03:16:55.390	2005/06/16 03:17:37.000	00:41.610	5000
2005/06/16 03:29:44.930	2005/06/16 03:30:27.671	00:42.741	5500
2005/06/16 03:56:25.421	2005/06/16 03:57:14.953	00:49.532	6000
2005/06/16 19:51:48.281	2005/06/16 19:52:47.703	00:59.422	6500
2005/06/16 20:09:34.421	2005/06/16 20:10:47.546	01:13.125	7000

Table 2: Intra-platform communications – same *container*, HTTP.

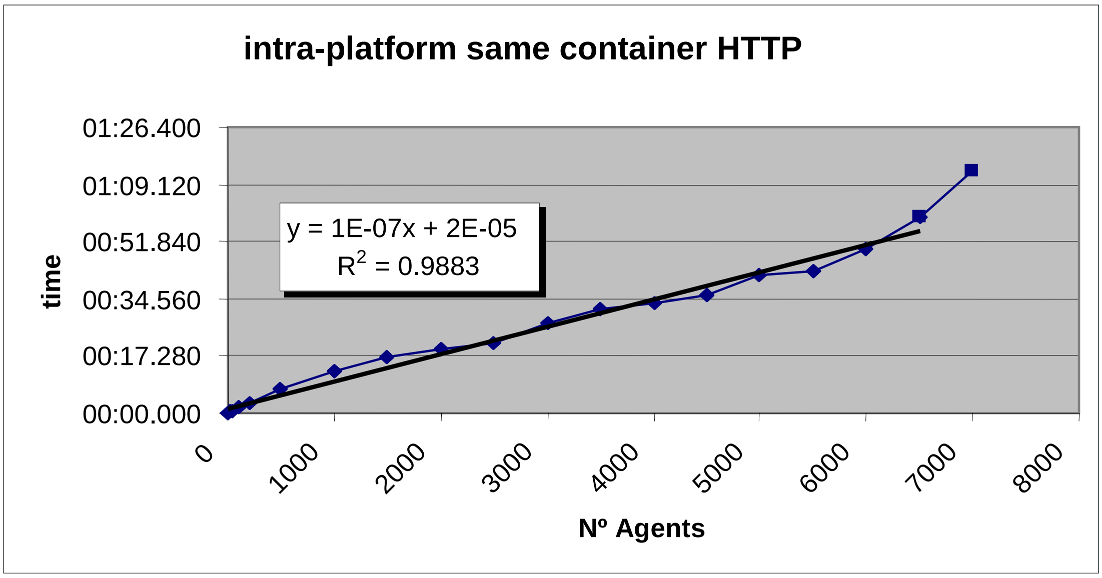

Figure 10: Intra-platform communications – same *container*, HTTP.

Sun ORB

The IIOP protocol address is called *Interoperable Object Reference* (IOR) and may contain one or more profiles, which describe how a client may contact and send requests to objects using a given protocol.

Until JADE 3.1, Sun IIOP was the default MTP used by JADE for inter-platform communications, while HTTP required an add-on. To launch JADE with Sun IIOP it is necessary to execute the command:

- `java -Xms64M -Xmx512M jade.Boot -mtp jade.mtp.iiop.MessageTransport Protocol`

The option `-mtp` specifies the MTP to be used, Sun IIOP in this case.

The simulation is similar to the previous one (and in this case results are also similar).

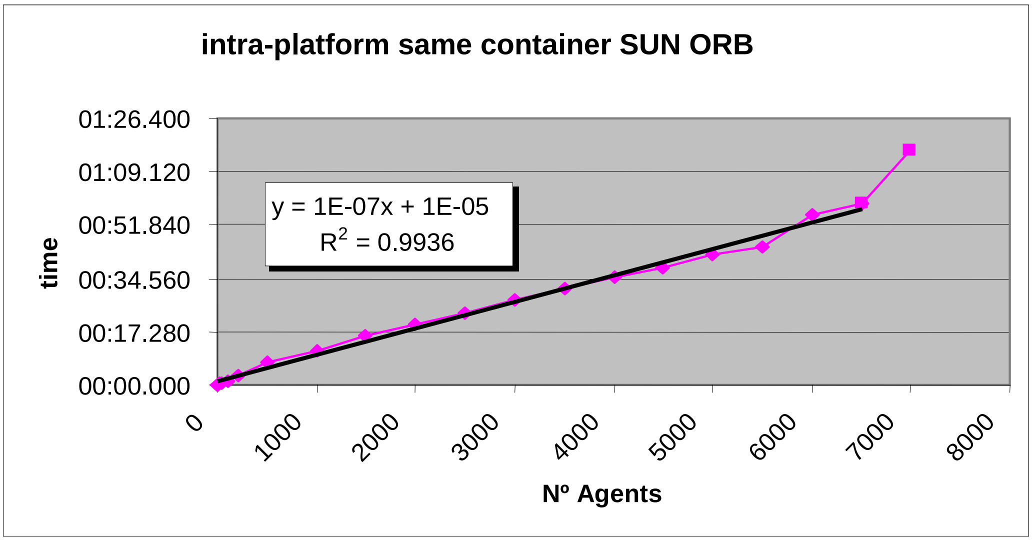

Figure 11: Intra-platform communications – same *container*, SUN ORB.

ORBACUS

The ORBACUS IIOP MTP supports three types of addresses – IOR, *corbaloc* and *corbaname*. In this case, a *corbaloc* address (`corbaloc:`*`proto`*`:`*`hostname`*`:`*`port/objectID`*) was used.

To launch JADE with ORBACUS it is necessary to execute the command:

- `java -Xms64M -Xmx512M jade.Boot -mtp orbacus.MessageTransportProtocol(corbaloc:iiop:inesc:1200/JADE)`

The simulation is similar to the previous ones (and in this case results are also similar).

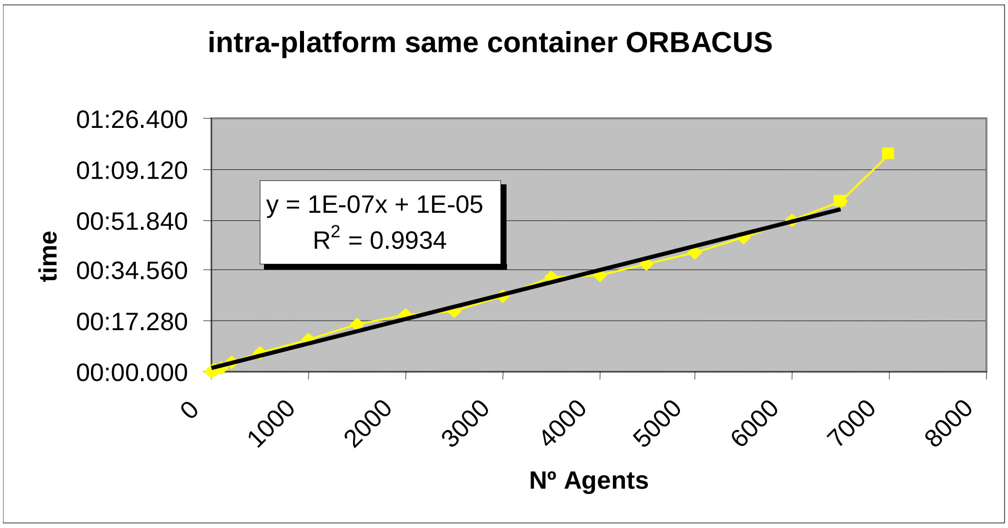

Figure 12: Intra-platform communications – same *container*, ORBACUS.

Conclusion

For intra-platform communications, with agents residing in the same container, performance is independent of the MTP, as shown by the simulation results and the corresponding figures, since JADE only uses direct event passing. As seen in the graphs, the simulation time as a function of the number of agents is well approximated by a linear function (with correlation factor close to 1), up to a number of agents around 6500.

4.4.1.2 Communication between different containers

In this case, the *Responders* and the *Initiator* reside in different containers. The Exchange of messages is done by means of Remote Method Invocation (RMI).

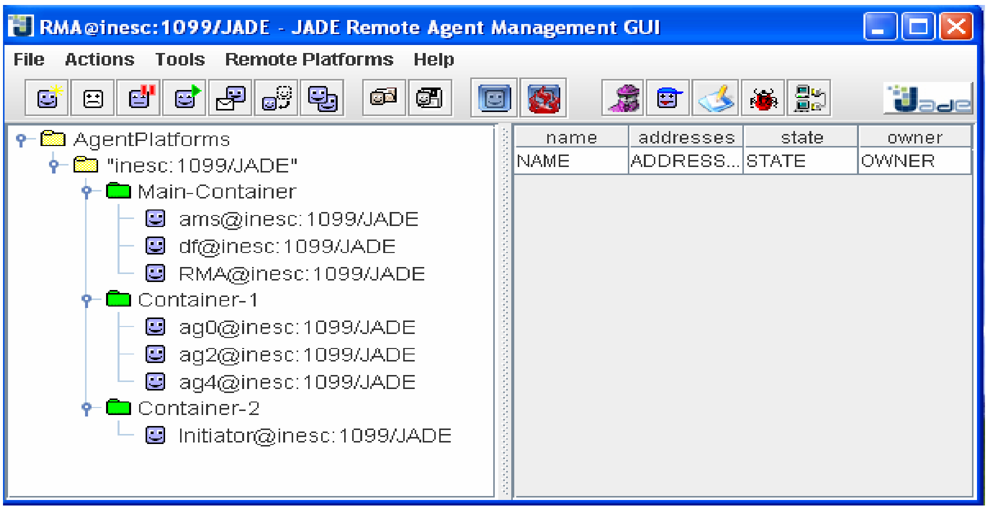

Figure 13: Launching of agents in different *containers*.

Launching the platform and Java applications is similar to the single container case; however the Java applications are different, since these applications allow launching the *Initiator* and the *Responders* in different containers (Figure 13).

Figures 14, 15 and 16 show the simulation results for the three MTPs under analysis.

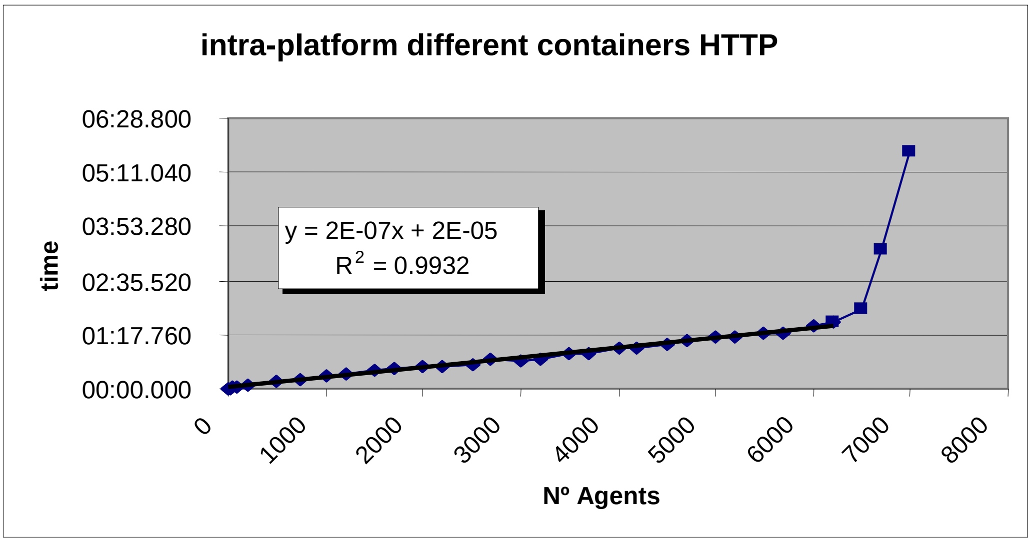

Figure 14: Intra-platform communications – different *containers*, HTTP.

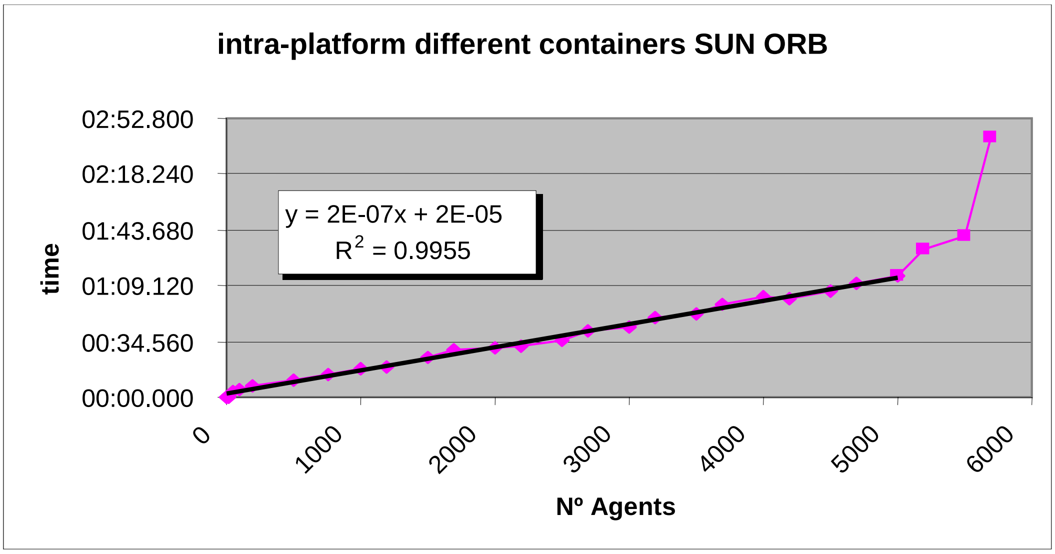

Figure 15: Intra-platform communications – different *containers*, SUN ORB.

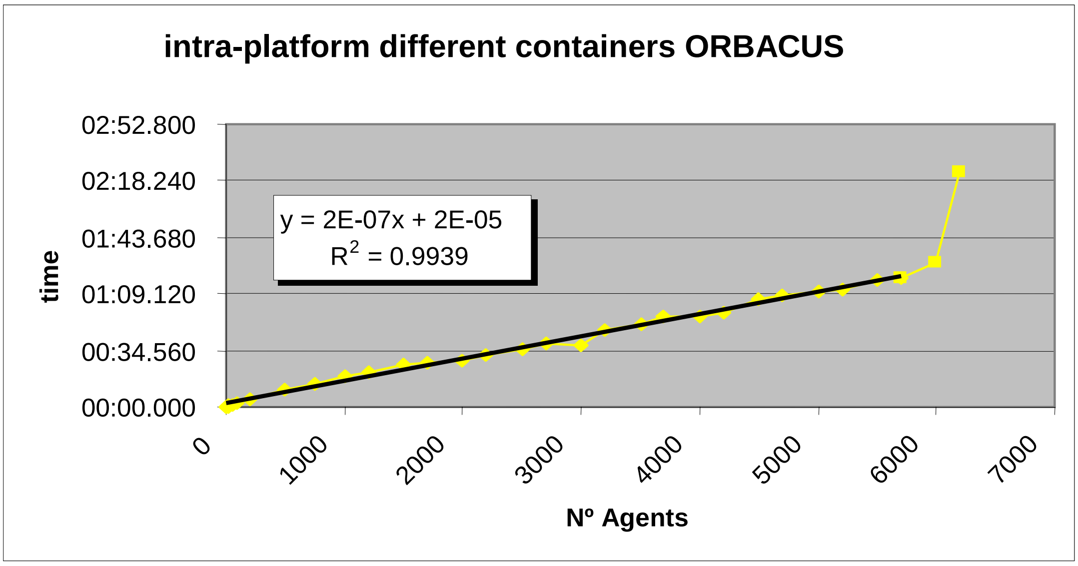

Figure 16: Intra-platform communications – different *containers*, ORBACUS.

<u>Conclusion</u>

Although JADE uses RMI for the exchange of messages between agents in different containers in the same platform (and not an MTP), the behaviour is different when the platform is launched with different MTPs.

A first conclusion is that HTTP shows the best performance, that is, it supports a higher number of agents without noticeable degradation. For the cases of Sun ORB and ORBACUS, degradation starts to occur for 5700 and 6200 agents, respectively, due to shortage of memory (hardware limitation of the system). In fact, HTTP requires less memory, especially in what concerns the address allocated to each agent, and confirms the choice of HTTP as the current default MTP in JADE.

Below the critical point, similar behaviour is observed in the three cases under analysis (similar correlation factors in the region where a linear approximation holds).

Figure 17 provides a direct comparison of all three MTPs for the case of different containers.

For all MTPs, performance with two containers is worse than for the single container case, as expected. Since HTTP has shown the best results, the comparison is shown in Figure 18, based on the results previously presented.

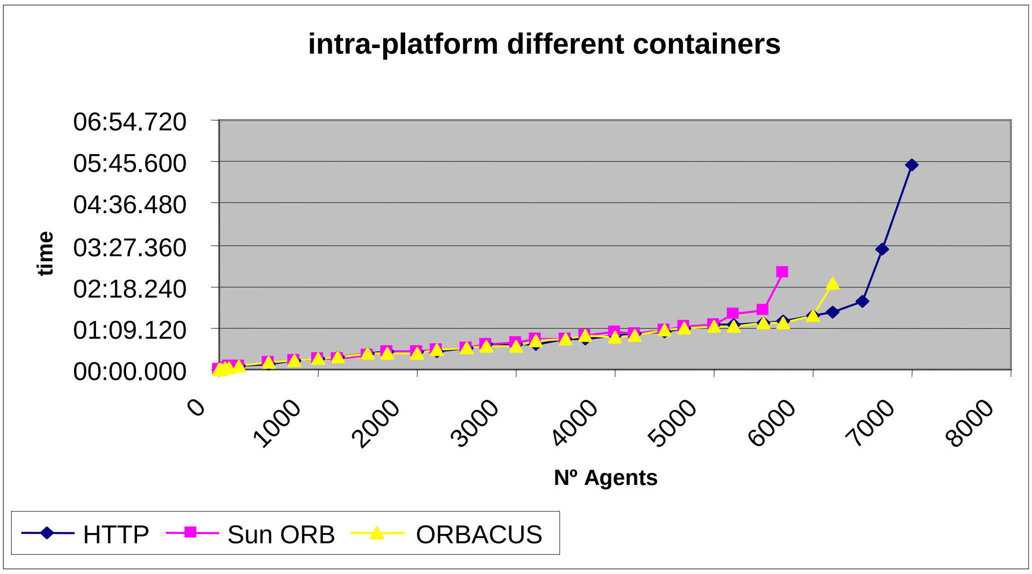

Figure 17: Intra-platform communications – different *containers*, all MTPs.

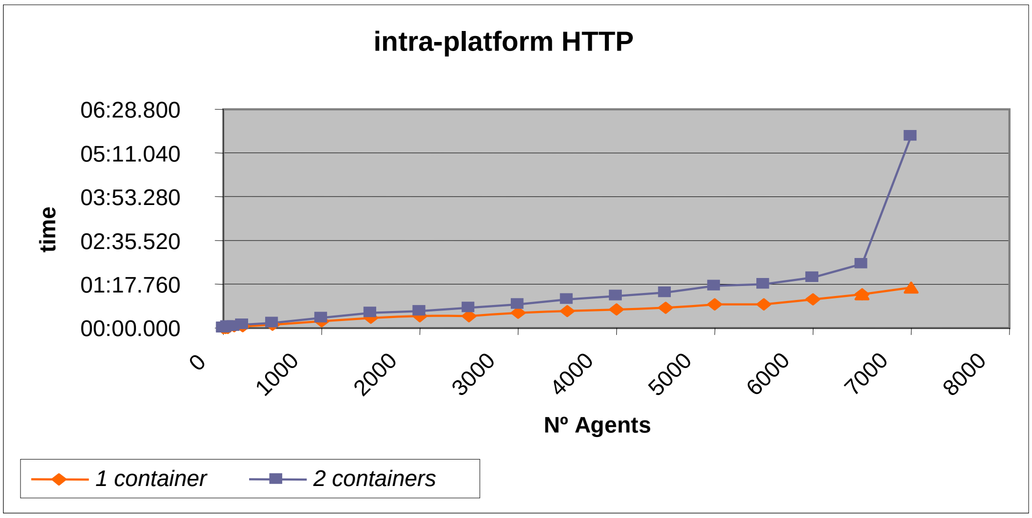

Figure 18: Intra-platform communications – one vs. two *containers*, HTTP.

4.4.2 Inter-platform communications

In the case of inter-platform communication, JADE actually uses MTPs and therefore performance of the selected MTPs is really compared.

Two scenarios were considered. In the first one, two JADE platforms were located in the same machine while, in the second one, the platforms were installed in two machines.

The Java applications used in the intra-platform scenarios were modified, as well as the agents that execute the Contract Net Protocol. The Java applications launch the agents in different platforms and the *Responders* have to register in the DF, so that the *Initiator* can find them. This method enables communication between agents in different platforms.

It is necessary, in the *setup()* method of the *ContractNetResponderAgent* program, to register all the *Responders* in the DF. To locate the participating agents, the *Initiator* must search the agents registry service in the *setup()* method of the *ContractNetInitiatorAgent* program.

4.4.2.1 Communication in the same machine

Computer A was used for the communications in the same machine. Configuration details and simulation results for the three MTPs are given next.

<u>HTTP</u>

The JADE platforms were launched in two different ports, with the commands executed in separate consoles (Figure 19). In the first command the default port (1099) is assumed.

- `java -Xms64M -Xmx512M jade.Boot -gui`
- `java -Xms64M -Xmx512M jade.Boot -gui -port 1100`

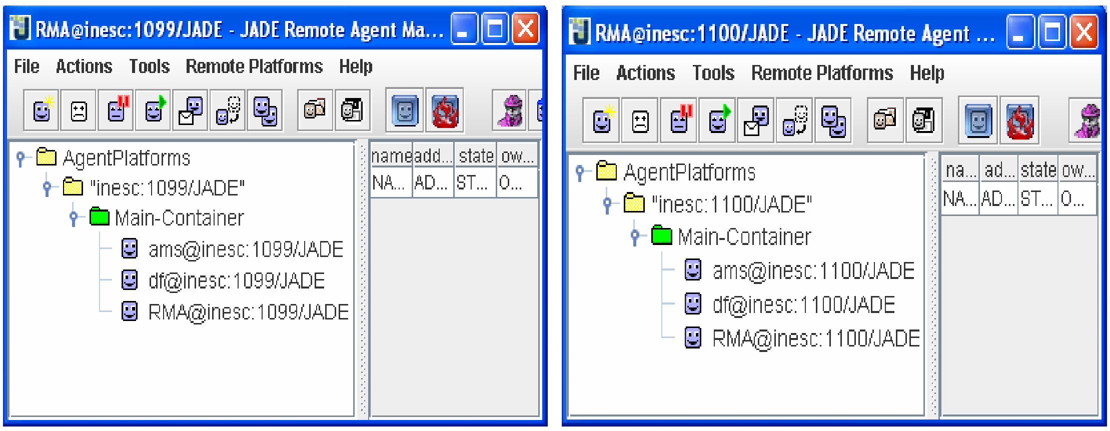

Figure 19: Launching of platforms in different ports.

The association of the DFs is then made, using the *menu Tools* of the JADE platform on port 1099, and selecting the option *Show the DF GUI* (Figure 20).

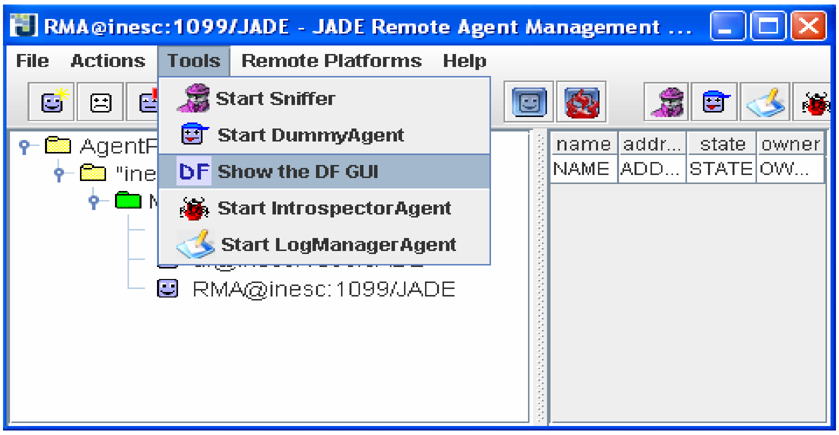

Figure 20: Opening of DF graphical interface.

The user must provide the name of the DF of the platform launched on port 1100 (`df@inesc:1100/JADE`) and its address (for example, http://inesc:1277/acc), as shown in Figure 21.

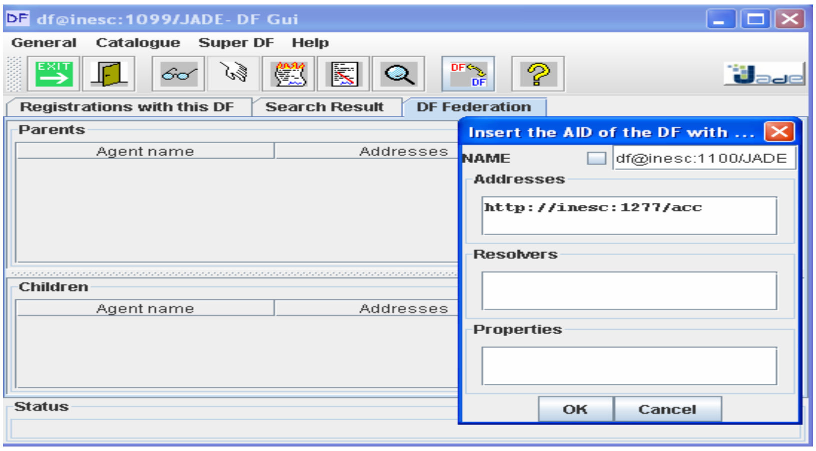

Figure 21: DF configuration.

After completing the above tasks, the DF of platform 1099 is associated with the DF of platform 1100. Therefore, the DF of platform 1100 is the ancestor of the DF of platform 1099. The relationship between DFs is visualized in Figure 22.

The Java applications are then run so that the CNP protocol is executed with the intended number of agents. They allow the creation of a *container* with the *Responders* in the platform launched on port 1099 (Figure 23) and a *container* with the *Initiator* in the other platform (Figure 24).

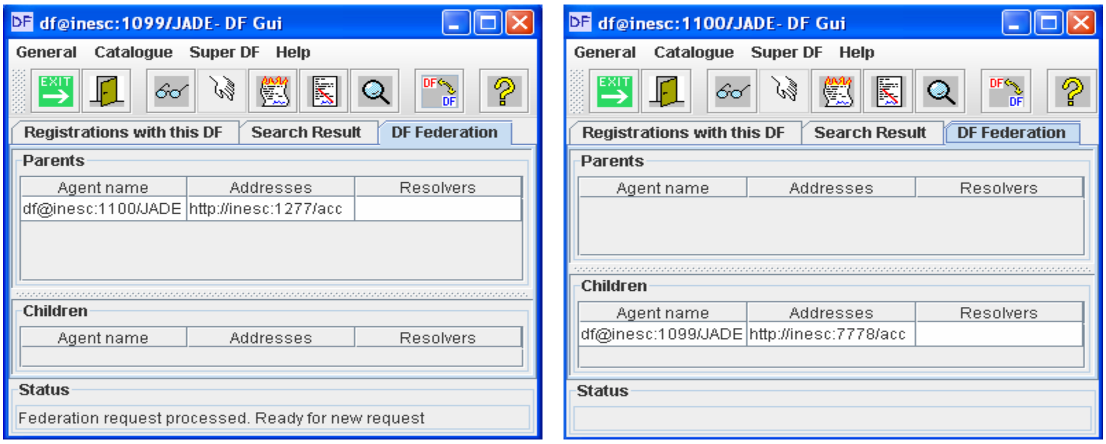

Figure 22: Relationship between DFs.

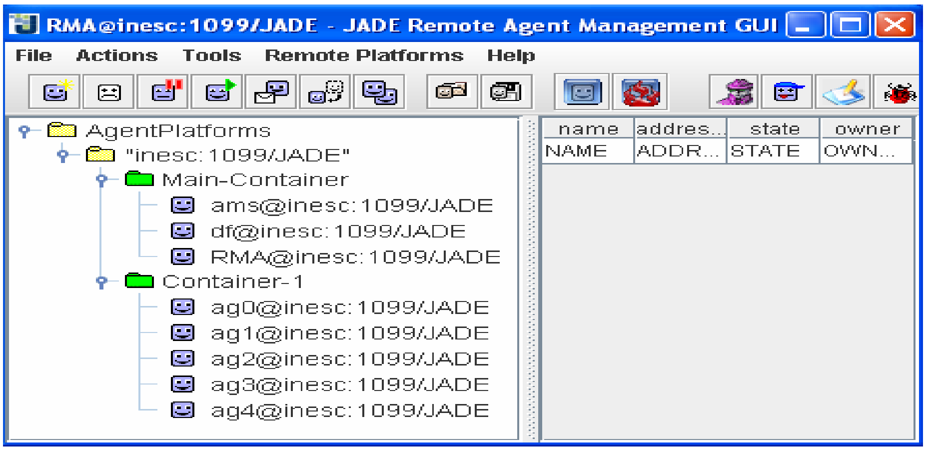

Figure 23: Launching of *Responder* agents.

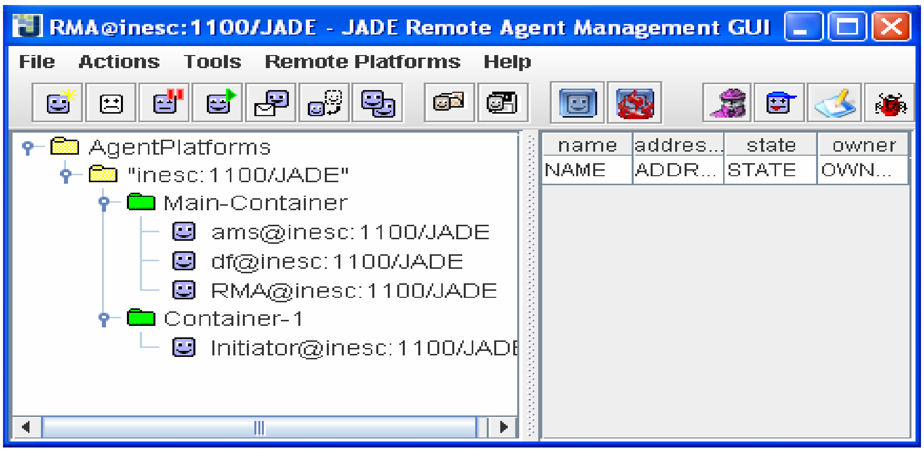

Figure 24: Launching of the *Initiator*.

The results shown in Figure 25 were obtained after running the simulations.

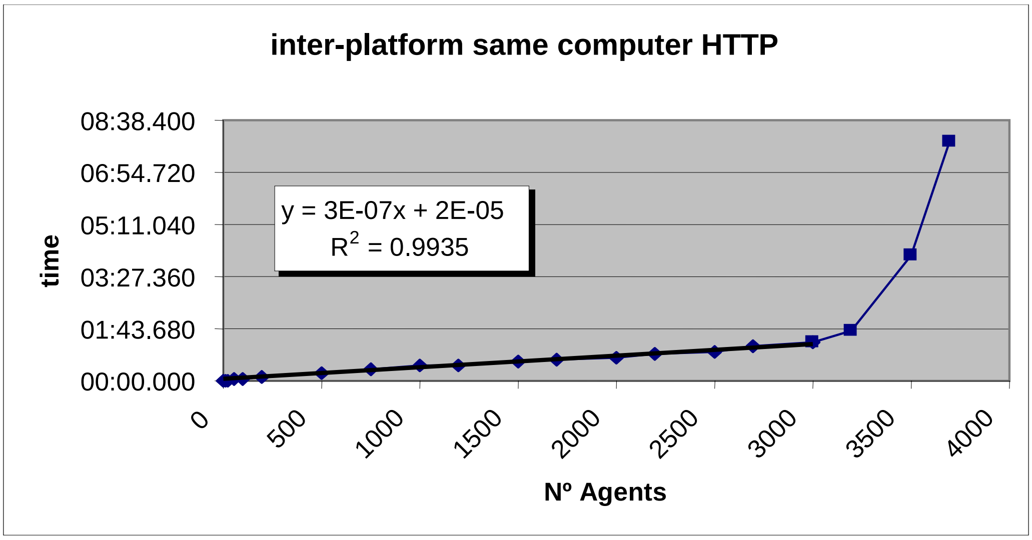

Figure 25: Inter-platform communications – same computer, HTTP.

<u>Sun ORB</u>

To launch the platforms the following commands are necessary:

- `java -Xms64M -Xmx512M jade.Boot -mtp jade.mtp.iiop.MessageTransportProtocol -gui`
- `java -Xms64M -Xmx512M jade.Boot -mtp jade.mtp.iiop.MessageTransportProtocol -gui -port 1100`

The address of each platform is now an IOR and not and HTTP URL. When associating DFs, the field Addresses of the platform on port 1099 must be filled with the IOR of platform on port 1100 (Figure 26).

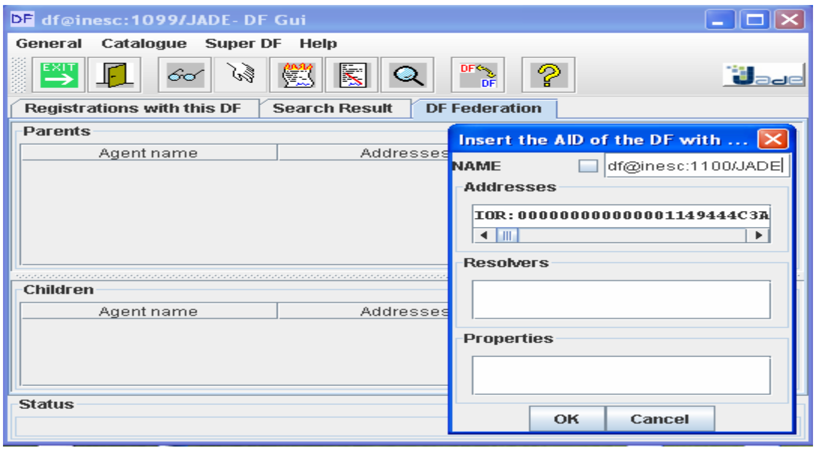

Figure 26: DF configuration.

The simulation results are shown in Figure 27.

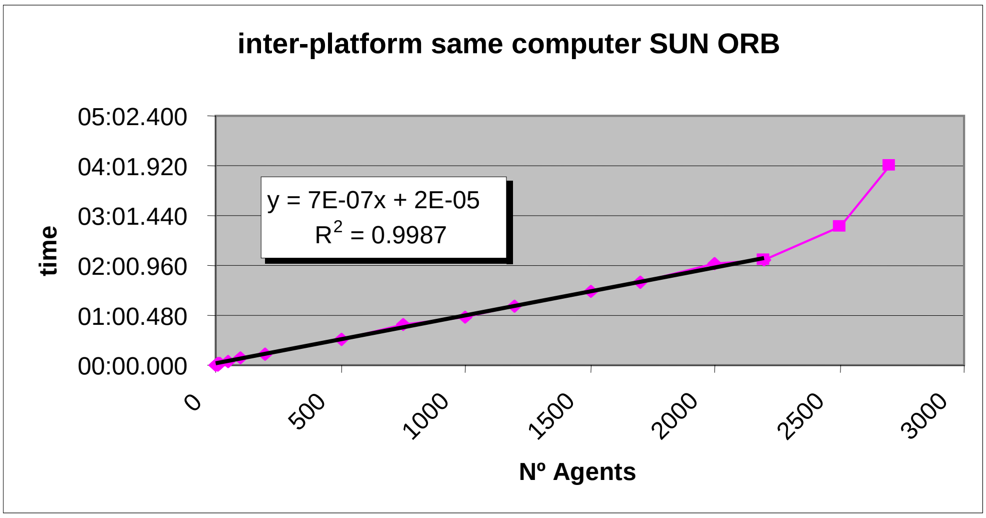

Figure 27: Inter-platform communications – same computer, SUN ORB.

<u>Orbacus</u>

To launch the platforms the following commands are necessary:

- `java -Xms64M –Xmx512M jade.Boot -mtp orbacus.MessageTransportProtocol(corbaloc:iiop:inesc:1200/JADE)`
- `java -Xms64M –Xmx512M jade.Boot -mtp orbacus.MessageTransportProtocol(corbaloc:iiop:inesc:1300/JADE)`

The address of each platform is a *corbaloc* address.

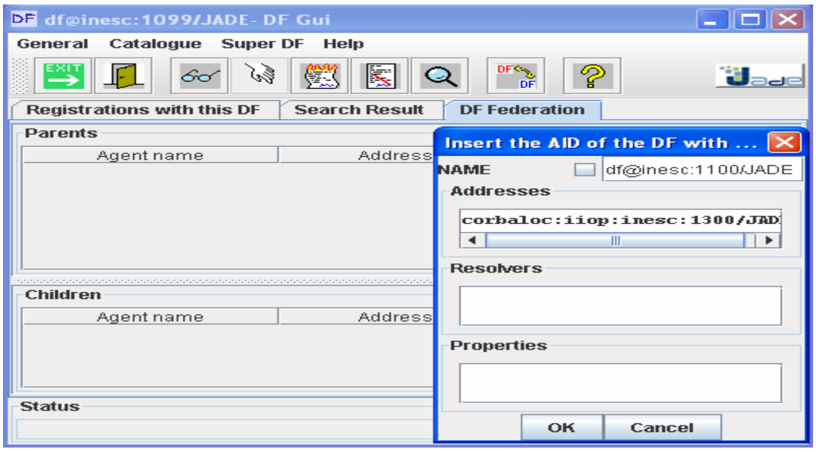

Figure 28: DF configuration.

The simulation results are shown in Figure 29.

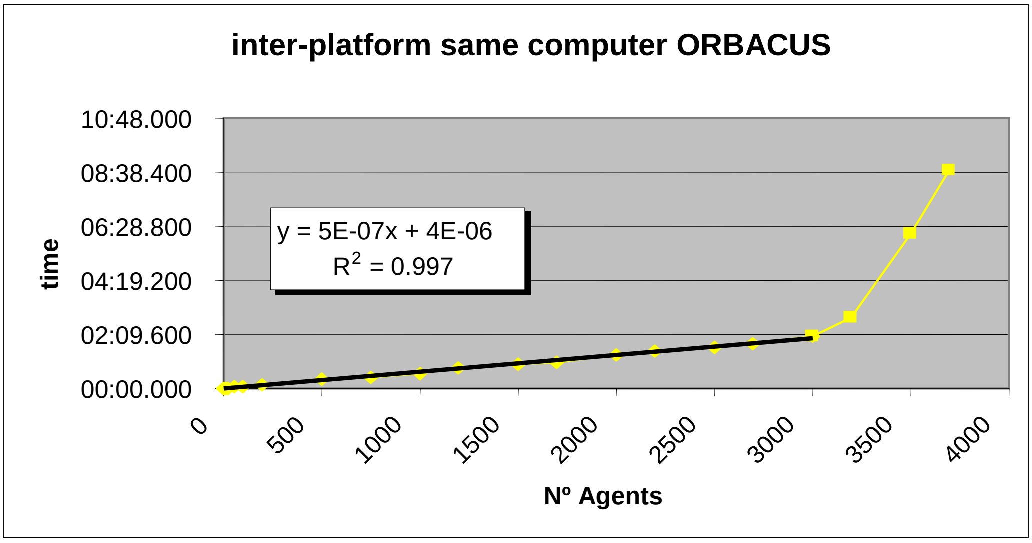

Figure 29: Inter-platform communications – same computer, ORBACUS.

<u>Conclusion</u>

For inter-platform communications, with agents residing in the same computer, performance depends on the MTP. Performance is better with HTTP and worse with SUN ORB, and degradation is also less pronounced with HTTP, as shown in Figure 30.

Moreover, performance is worse than in the intra-platform case, for all MTPs, which is revealed by a higher negotiation (response) time and a lower number of agents supported.

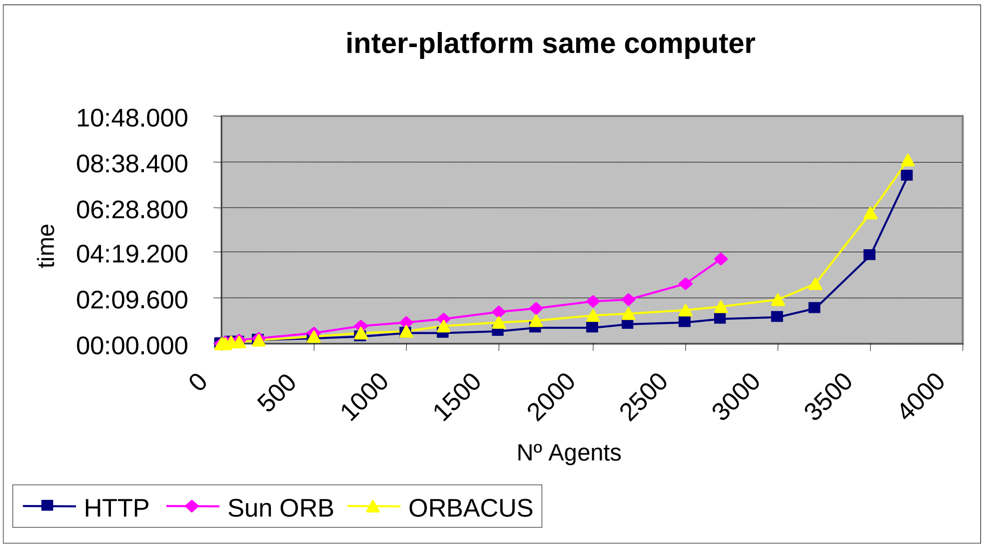

Figure 30: Inter-platform communications – same computer, all MTPs.

4.4.2.2 Communication between different machines

In this case both computers A and B were used.

The JADE platforms are launched in different machines (Figure 31), both in port 1099 (default), and then the Java applications are launched on machine A. Simulation is similar to the previous case, with the same commands for each MTP

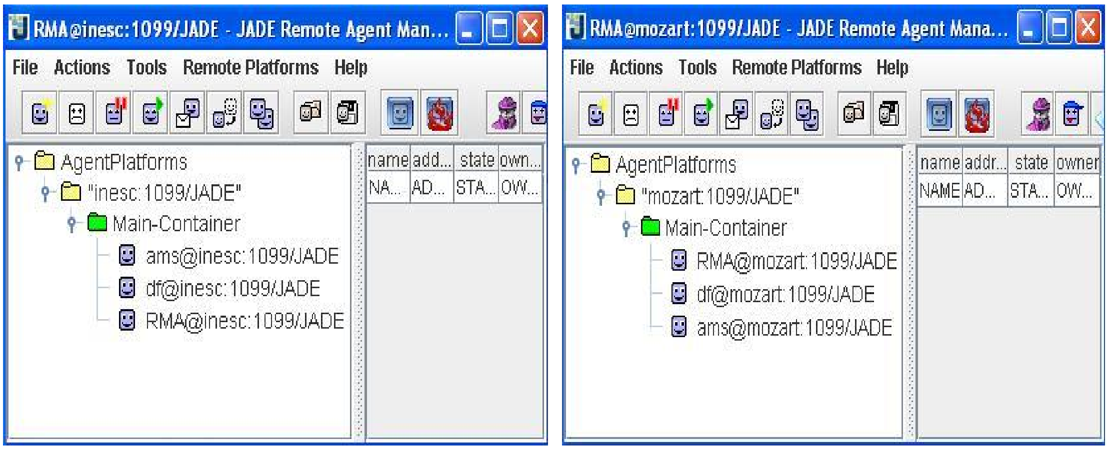

Figure 31: Launching of platforms in different computers.

Figures 32, 33 and 34 show the simulation results for the three MTPs under analysis.

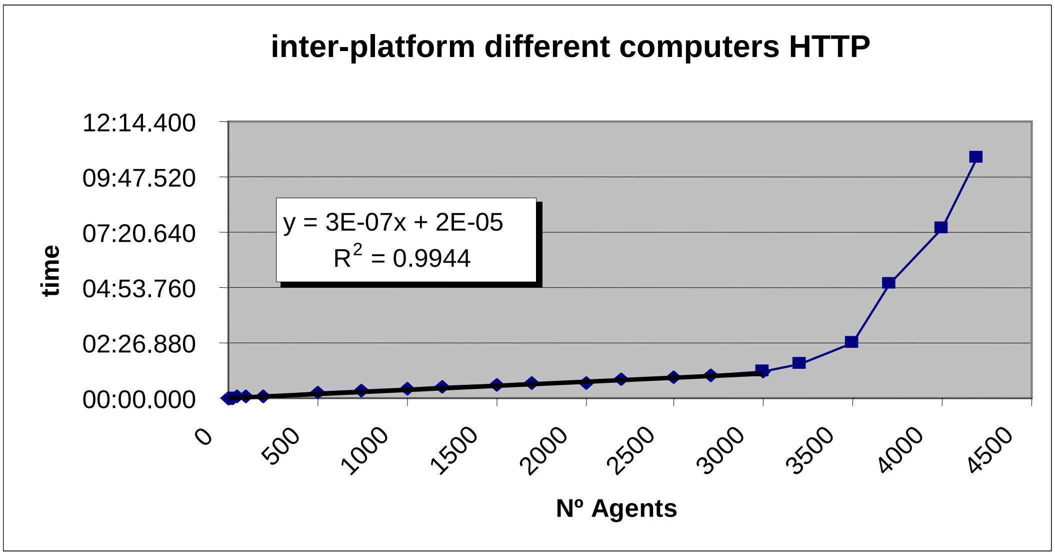

Figure 32: Inter-platform communications – different computers, HTTP.

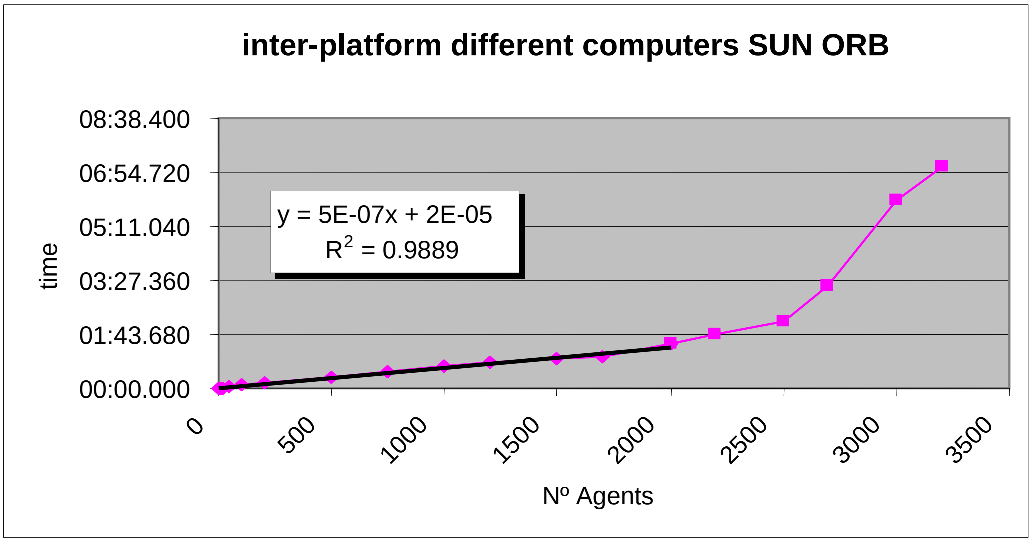

Figure 33: Inter-platform communications – different computers, SUN ORB.

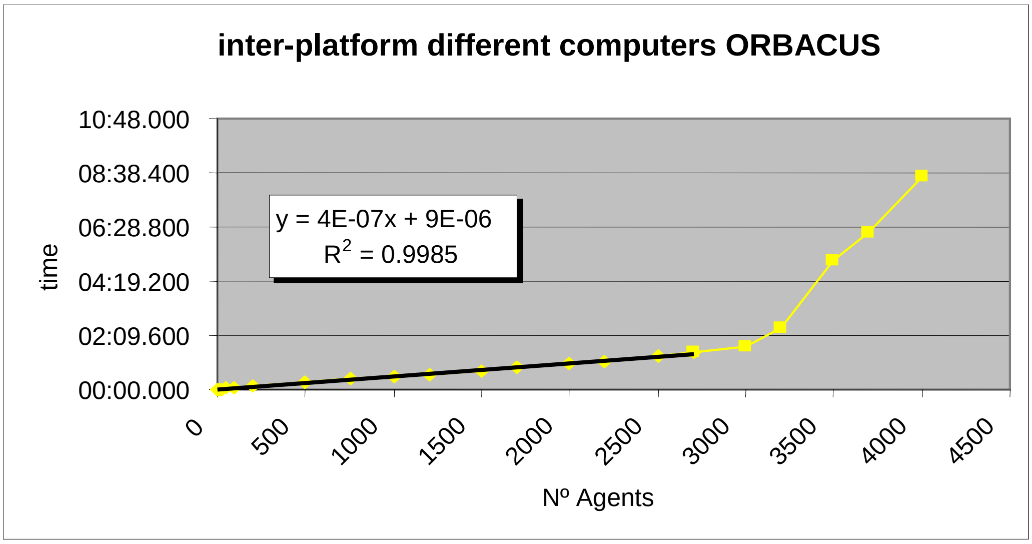

Figure 34: Inter-platform communications – different computers, ORBACUS.

<u>Conclusion</u>

Once again it is possible to conclude that HTTP is the best choice, as shown on Figure 35 that compares all three MTPs. The results are worse than for the single platform case.

Another conclusion is that performance is better in the case of the containers residing in two computers, since the computational load is divided between two machines. This is shown in Figure 36 for HTTP.

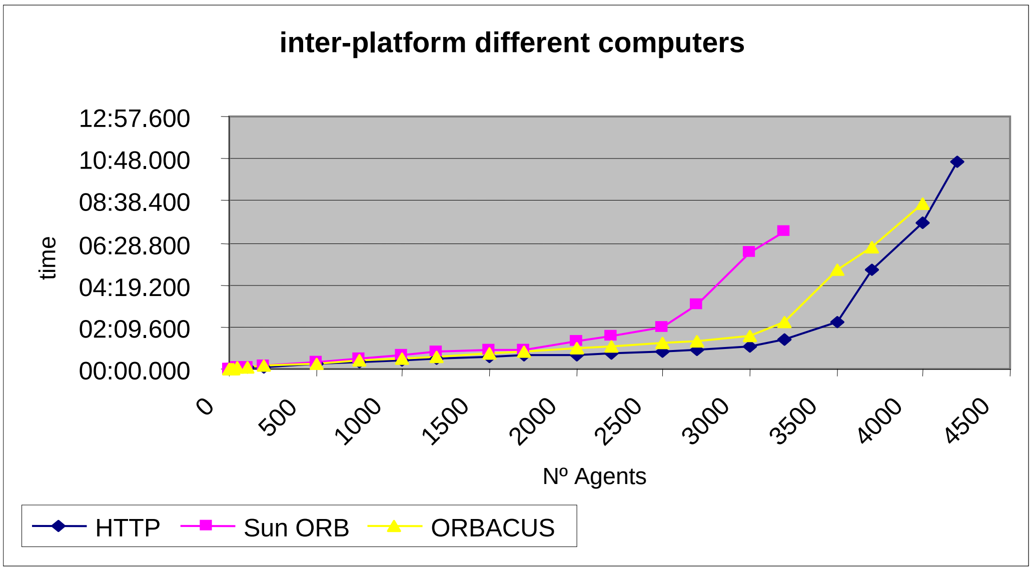

Figure 35: Inter-platform communications – different computers, all MTPs.

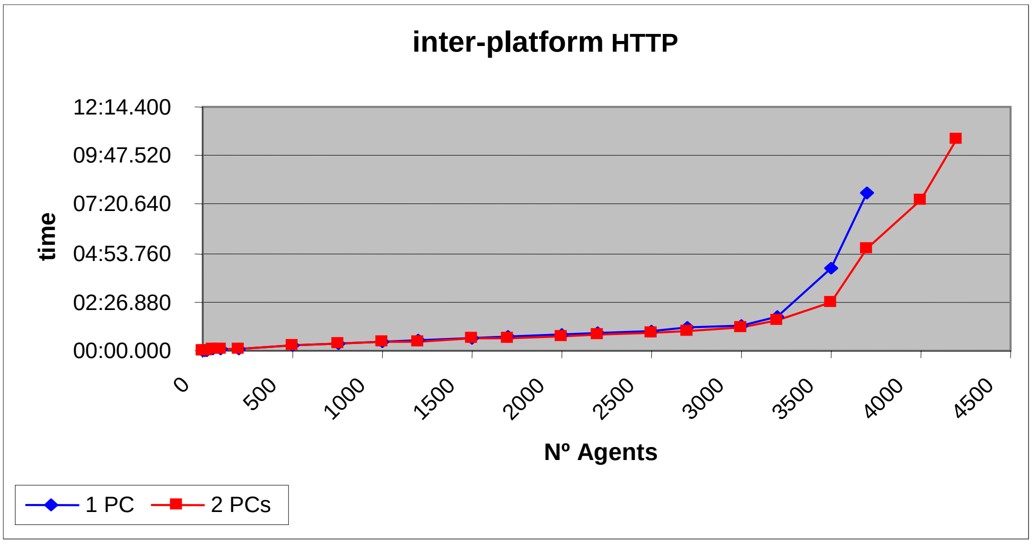

Figure 36: Inter-platform communications – one vs. two computers, HTTP.

4.4.3 Intra versus inter-platform

In this section the results previously presented are organized in a different way to provide a comparison between intra-platform and inter-platform communications.

Since in all cases analysed HTTP proved to be the best choice, the comparison is only carried out for this case, but a similar behaviour occurs in the other cases.

The direct comparison is only meaningful when considering agents residing in two containers in the same computer, but distributed on one or two platforms.

The results are summarized in Figure 37.

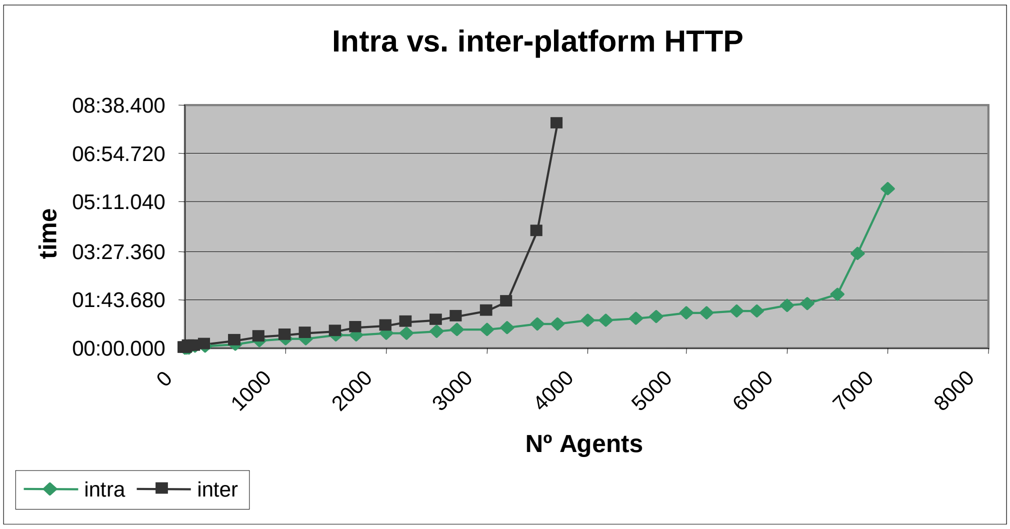

Figure 37: Intra vs. inter-platform communications – same computer, HTTP.

5 Evaluation summary

To assess the ability of the agents' architecture to fulfill MICROGRIDS requirements, a performance evaluation of the JADE platform was carried out from the points of view of response time and scalability.

Various communications scenarios were considered, both for intra and inter-platform communications. Three Message Transport Protocols (MTP) were used – HTTP, Sun ORB and ORBACUS (from IONA).

The *Contract Net Protocol* (CNP) was selected for the performance and scalability tests. The parameter of interest in the simulations was the *negotiation time* as a function of the number of participating agents.

For intra-platform communications, although no MTP is specified, the platform was launched with the three selected MTPs, in order to assess the behaviour of message passing. Two sets of tests were performed – agents residing in one container and in two containers (in the same computer), respectively.

In the first case, the choice of MTP is not relevant, since JADE only uses direct event passing. The negotiation time increases almost linearly with the number of agents and this was observed in tests with up to 7000 agents (with an average of 10 ms for a complete dialogue between the *Initiator* and each *Responder*).

With two containers, the choice of MTP influences the performance. Best performance is achieved with HTTP (and is worse with SUN ORB); this is observed both in the accumulated negotiation time and in the point where degradation starts to occur, which is shown by a sharp increase in the negotiation time (for HTTP, this occurs for about 6500 agents). This is certainly due to the fact that HTTP uses less memory to allocate addresses to agents and confirms the choice of HTTP as the current default MTP in JADE. As expected, performance is worse than for the single container case.

For inter-platform communications two sets of tests were carried out, as well – agents residing in two platforms in the same computer and agents residing in two platforms in different computers. Performance is worse than in the intra-platform case for all MTPs, that is, there is a higher negotiation (response) time and a lower number of agents supported when degradation becomes noticeable (for HTTP this occurs for about 3500 agents). Once again, performance is better and degradation less pronounced with HTTP and worse with SUN ORB. Performance is better when the containers reside in two computers, since the computational load is divided between the machines.

A study with similar goals is described in the paper "Scalability and Performance of the JADE Message Transport System" and was carried out by TILAB researchers. Test conditions were different (based on a circular exchange of messages), and only two MTPs were used (SUN ORB and ORBACUS). The present study confirmed the trends identified in that study for these two MTPS but was extended with HTTP, which proved to be the best choice.

The main conclusions of this study are briefly summarized:

- Best performance is achieved for communications within a container (intra-platform).
- When agents run in containers in different platforms (inter-platform), best results are achieved when containers reside in different machines.
- HTTP is the best choice for the Message Transport Protocol, especially for the case of inter-platform communications.
- Results have shown excellent scalability properties, which allows concluding that JADE is capable of fulfilling MICROGRIDS requirements.

6 References

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