WireNet: An Experimental System for In-House Power Line Communication

Geir Mathisen (1) and Andrea M. Tonello (2)

(1) SINTEF ICT - NO-7465 Trondheim – Norway, and Norwegian University of Science and Technology - NO-7491 Trondheim – Norway
phone: +47 735 94367 – e-mail: geir.mathisen{@sintef.no, @itk.ntnu.no}
(2) DIEGM - Università di Udine - Via delle Scienze 208 - 33100 Udine – Italy
phone: +39 0432 558042 – e-mail: tonello@uniud.it

Abstract— **This paper describes the main experimental results that have been obtained with a prototype system developed within a Craft project in the EU Growth Programme: WireNet-"Powerline data exchange for domestic and industrial automation based on the Ultra Wide Band (UWB) approach". The project aimed at designing and realising an innovative system for power-line data exchange using some concepts derived from the UWB technology, and in particular, the wide band impulse modulation solutions. The WireNet system targets several application scenarios such as low-data rate home/industrial automation and moderate data rate applications such as voice and audio streaming. Stringent constraints on complexity and overall cost have been set. This has motivated the investigation of simple, though performance wise good, transmission solutions. The paper gives a description of the main principles behind the adopted wide band impulse modulation solution and the protocol specifications. Moreover, a description of the hardware prototype together with a presentation of the performed tests, is given. The experimental results show that the WireNet system allows for reliable communications in indoor powerline scenarios with a simple wideband transmission scheme that is robust in the presence of highly frequency selective channels and background disturbances.**

Keywords—**Experimental systems, field trials, hardware prototype, impulse modulation, wideband powerline systems.**

I. INTRODUCTION

In this paper we report the main experimental results that have been obtained with a prototype system for indoor communications. The experimental system has been developed within a Craft project in the EU Growth Programme: WireNet, "Powerline data exchange for domestic and industrial automation based on the UWB approach". The project has involved the following partners: Nobo (Norway), Dunvegan (UK), Microtelecom (Italy), Isomatic (Bulgaria), JG Componentes (Portugal), Ardoran (Estonia), Alfa Sistemi (Italy), Labor (Italy), University of Udine (Italy). The main achievements have been to investigate, in a specialised laboratory set-up, the fundamental aspects of the wide-band impulse modulated solution, prototype and test specialised hardware components, develop a physical layer, a MAC and a link layer, demonstrate the exploitation potential of the technology by means of a demonstrator that is focused on a low-cost system for home and industrial applications.

The general challenges with power line communication are based on the variation of impedances on power lines and the presence of unpredictable noise. This variation is not only dependent on the specific power line, but also time dependent as electrical equipment are connected and disconnected to the power line, or permanently connected devices are activated and deactivated. As equipment connected to the power line may use capacitors to prevent generated noise to propagate into the power line, these capacitors also damp the communication signals. Hair dryers, light dimmers, fluorescent lamps, not to mention industrial frequency converters and lift engines, send spikes of static coursing back through the wires which can overshadow the communication signals.

The WireNet project met extra challenges in terms of having participants from all over Europe that had the requirement of satisfying different power grid configurations. A further requirement was that the communication solution had to cover a variety of applications ranging from systems with many nodes, with low need for data rate, with low price and power consumption, to systems with few nodes continuously streaming data at high rate. As a result the system targets several application scenarios such as low data rate home/industrial automation (below 500 kbit/s) and higher data rate applications above 2 Mbit/s such as audio, and video. Stringent complexity and consequently cost constraints were also established. This has motivated the investigation of simple, though performance wise good, transmission solutions.

In the WireNet project we have considered the use of wide band (beyond 20 MHz) impulse modulation. Up to date, impulse modulation has been mostly considered for application over wide band wireless channels [1]. It shows interesting properties in terms of simple baseband implementation, and robustness against frequency selective fading and interference. The basic idea behind impulse modulation is to convey information by mapping an information symbol stream into a sequence of short duration pulses. No carrier modulation is required. Pulses (referred to as monocycles) are followed by a guard time in order to cope with the channel time dispersion. The monocycle can be appropriately designed to shape the spectrum occupied by the transmission system. Wide band impulse modulation allows to use a simple matched filter receiver that correlates the received signal with a template waveform. Simple synchronization and channel estimation algorithms can be deployed [2]. Performance wise, this solution allows to exploit the channel diversity and operate at low signal-to-noise ratios. This is because each data symbol is spread via the shaping waveform over a broad band. The use of the guard time allows to simplify the equalization task. Finally, the simple matched filter receiver allows to optimally collect the wide band channel energy [3].

The paper gives a description of the principles of the transmission scheme, it describes how applications are grouped into classes and describes the current version of the WireNet protocol. Moreover, we report the main features of the WireNet prototype that we have developed together with a presentation of the performed tests.

II. APPLICATIONS AND THE INFLUENCE OF THESE ON THE REQUIREMENT

The WireNet project has involved seven industrial participants, all bringing into the project applications relevant for their business concept. The applications can be grouped as follows: Home/industrial automation and control systems; Building management systems; Digital audio and video transmission systems; Emergency communication systems. Intuitively, this list of application indicates a large span of needed transmission rate. It also shows that the different application systems deploy different overall number of nodes. Moreover the cost sensitivity of the different systems, and the allowed power consumption are also different. Fortunately, the sum of requirements is still manageable. Table I shows a systematic treatment of the requirements. Another important issue is to assure coexistence between different equipment and applications connected to the same power line segment.

Application	Transmission Rate	Cost Sensitivity	Power Consumption Sensistivity	Number of Nodes in a System
Home and industrial control	Low	High	High	Many
Building management	Medium	High/Medium	High/Low	Medium
Digital audio/video	High	Low	Low	Few
Emergency comm..	Medium/High	Low	Low	Medium/Few

Table I: Requirements related to group of applications.

Based on the above considerations the applications have been classified and grouped as follows:

- **Highly restricted transmitting equipment class (HRTC).** Equipment of this class is only allowed to occupy the channel for up to 3 ms in a frame of 1 s, and maximum 1 ms continuously.
- **Slightly restricted transmitting equipment class (SRTC).** Equipment of this class is only allowed to occupy the channel for up to 30 ms in a frame of 1 s, and maximum 1 ms continuously.
- **Unrestricted transmitting equipment class (URTC).** Equipment of this class has no restriction concerning occupying the channel, except for not allowing to occupy the channel for more than 1 ms continuously.

The equipment itself can in principle define which class to be a member of, based on the current need for communication, and the actual communication for the last 5 s. This implies that equipment can momentarily change class membership from HRTC to SRTC/URTC, or from SRTC to URTC. Moreover, equipment can change class membership from URTC to SRTC or HRTC based on the current and the last 5 s of communication.

III. DESCRIPTION OF PROTOCOL

The WireNet protocol can be divided into five layers:

- Physical layer. It describes the transmission interface.
- Electrical layer. It describes the electrical connection between the power line and a WireNet module.
- Bus arbitration and channel occupation layer. This layer describes how to take the channel for transmission, and the rules about channel time occupancy.
- Frame layer. It describes how the information bits of a WireNet frame are used.
- Net structure layer. The structure of the WireNet system, as seen from a node, is divided into two parts; the local area which the node is a member of, and the overall net.

A. *WireNet Physical Layer and Channel Modeling*

In the WireNet system communication is from one node to another node such that if other nodes simultaneously access the medium they are seen as potential interferers. The media access scheme is a prioritized random scheme (see below). Each node deploys adaptive wide band impulse modulation (Fig.1). The modulation scheme uses multilevel amplitude impulse modulation. The signal transmitted by user *u* is

$$s^{(u)}(t) = \sum_k c_k^{(u)} g(t - kT_f^{(u)}) \qquad (1)$$

where $g(t)$ is the waveform (monocycle) used to convey information and $c_k^{(u)}$ is the information symbol that is transmitted during the *k*-th frame of duration $T_f^{(u)}$. $\log_2 M^{(u)}$ bits are mapped into a symbol whose alphabet is equal to $[\pm 1, \pm 3.., \pm(M^{(u)} - 1)]$. We assume to use a monocycle with short duration D and a frame of duration $T_f^{(u)} = D + T_g^{(u)}$. Both the amplitude modulation order and the guard time length can be adaptively chosen for the user *u*. They are adapted according to the rate requirement and the channel state. In particular, the guard-time length $T_g^{(u)}$ can be chosen longer than the channel time dispersion such that we can avoid inter-symbol interference (ISI) at the receiver. More in general, it is chosen to control the amount of ISI such that we can simplify the equalizer complexity. It follows, that user *u* transmits $\log_2 M^{(u)} / T_f^{(u)}$ bits/s. The monocycle can be appropriately designed to shape the spectrum occupied by the transmission system. If for instance, we use the second derivative of the Gaussian pulse, the spectrum does not occupy the low frequencies where we experience higher levels of man-made noise (see Fig. 2 where the -10 dB band is equal to about 30 MHz). Other pulse choices can be made.

Channel coding is also added. In particular, we have considered bit-interleaved convolutional codes. In Table I we summarize the raw data rates for some adaptive rate impulse modulation (ARIM) schemes. The information symbols are grouped into frames. In Fig. 2 we depict a frame when ARIM 1 is used. The frame has a duration of 292 us. The training bits are used for frame synchronization and channel estimation.

The simple receiver that we have implemented in the hardware prototype comprises the following stages. First, the received signal is filtered with a wide-band front-end filter. Then, it is sampled at rate 50 MHz. Digital signal processing is deployed to acquire frame synchronization and estimate the channel impulse response [2]. Finally, a digital matched filter (matched to the equivalent impulse response that comprises the transmit monocycle and the channel impulse response) is implemented. Symbol decisions are made at the output of the matched filter, or more in general, soft bit statistics are calculated and fed to the Viterbi convolutional decoder. An outer block code is also used for error detection. If the guard time is sufficiently long, we do not get any ISI at the matched filter output. Otherwise, we can deploy some form of equalization, e.g., simple linear equalization, to cope with the residual ISI.

Channel measurements have been made in typical indoor scenarios. We have found channel dispersion in the order of 2 us for node-to-node distance of about 100 m. An example of measured channel response is shown in Fig. 3. In Fig.3.D we plot the equivalent channel response that is obtained by convolving the monocycle with the channel response, and a receive filter matched to the monocycle. The equivalent response is significantly compressed because the monocycle filters out the low frequency components that are responsible for the longer channel delays. From the measurements we have derived a statistical channel model. The statistical model allows to capture the ensemble of network topologies, thus it is very useful to test via simulation the system performance. To derive the model, we start from the well-known band pass PL model in [4] where the frequency response is synthesized with N_P multipaths (echoes) as

$$H_+(f) = \sum_{p=1}^{N_P} g_p e^{-j\frac{2\pi d_p}{v}f} e^{-(\alpha_0+\alpha_1 f^K)d_p} \qquad 0 \le B_1 \le f \le B_2 \qquad (2)$$

where $|g_p| \le 1$ is the transmission/reflection factor for path p, d_p is the length of the path, $v = c/\sqrt{\varepsilon_r}$ with c speed of light and ε_r dielectric constant. The parameters α_0, α_1, K are chosen to adapt the model to a specific network. This, model can realistically represent a true frequency response. To capture the ensemble of PL grid topologies we add some statistical property to it. In particular, we assume the reflectors (that generate the paths) to be placed over a finite distance interval. We fix the first reflector at distance d_1 and we assume the other reflectors to be located according to a Poisson arrival process with intensity $\Lambda\ [m^{-1}]$. The reflection factors g_p are assumed to be real, independent and uniformly distributed in $[-1,1]$. Finally, we appropriately choose α_0, α_1, K to a fixed value. If we further assume $K=1$, the real impulse response can be obtained in closed form.

The impulse response can be assumed to be constant for a given amount of time. Then, it changes for a new (randomly

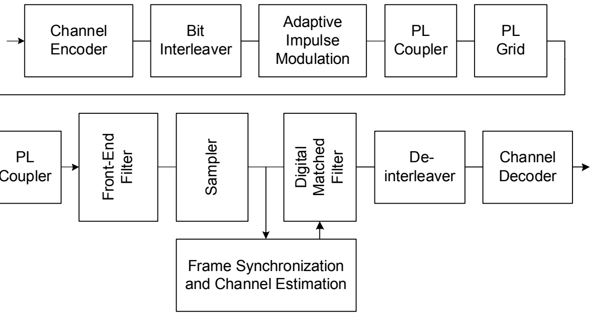

Fig. 1. WireNet physical layer.

	Modulation	Tf(ns)	Peak Bit Rate (Mbps)
ARIM 1	2-PAM	2000	0.5
ARIM 2	2-PAM	512	1.95
ARIM 3	4-PAM	512	3.90
ARIM 4	4-PAM	256	7.81

Table II. Some adaptive rate transmission schemes with pulse amplitude modulation (PAM).

1 Bit Guard 2 us	N_{TR}=48 Training Bits T_f=2 us	N_I=96 Information Bits T_f=2 us	1 Bit Guard 2 us

Fig. 2. Frame format.

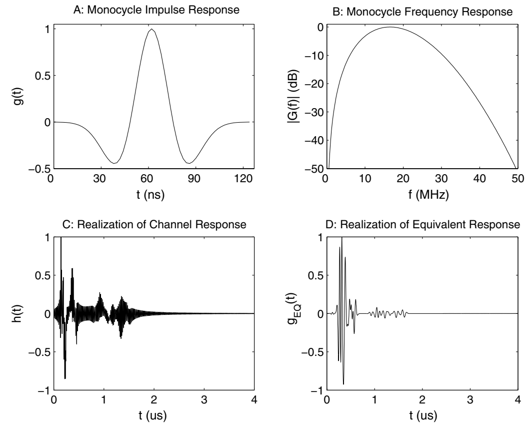

Fig. 3. Monocycle impulse/frequency response, and example of channel response and equivalent channel response.

picked) topology. An example of typical values for the parameters is as follows. B_1=0 and B_2=50 MHz. In a indoor environment where the number of paths is high, we fix for the underlying Poisson process an intensity $\Lambda=1/15\ m^{-1}$, i.e., one reflector every 15 m in average. The maximum distance is set at 300m, and we fix K=1, $\alpha_0=10^{-5}\ m^{-1}$, $\alpha_1=10^{-9}$ s/m.

A comparison between the simulation results and the real field test results has shown a close match. The performance results have shown that the scheme is very robust to channel frequency selectivity. This is due to the fact that in the proposed scheme each data symbol is transmitted with a low duty cycle and its energy is spread in frequency over a large bandwidth. This makes the demodulator less sensitive to frequency notches since it coherently combines the energy over a broad spectrum. Furthermore, the bit-interleaved convolutional code provides good performance in the presence of impulsive noise components.

B. *Electrical Layer*

The WireNet equipment is connected to the power line via a balanced wideband transmission line type coupler. The coupler has been designed such that it has a flat frequency response in the transmission bandwidth, and to achieve a good common mode rejection ratio. The transmit power is within the values given in the norms [5]-[6].

C. *Bus Arbitration and Channel Occupation Layer*

The channel arbitration mechanism when transmitting a frame is based on CSMA (carrier sense multiple access), with a random inter-frame time. The minimum time is determined by the class of the WireNet equipment (HRTC, SRTC, URTC), the kind of frame to be sent, and the maximum coverage distance (i.e., 300 m).

In addition to the transmitting time restrictions, the equipment of both the HRTC and SRTC are allowed to send *acknowledge frames*, if requested. The following minimum inter-frame time is used (from a frame-end to the next frame-start, in us):

- 10 Acknowledge frames on request
- 15 + (0<= random time < 20) HRTC frames
- 35 + (0<= random time < 20) SRTC frames
- 55 + (0<= random time < 20) URTC frames

D. *Frame Layer*

The frame layer specifies the allocation of the information bits. Here we describe the frame layer for the ARIM 1 scheme. Furthermore, we point out that in the hardware prototype to keep the complexity as low as possible we haven't implemented the convolutional code. A simple Hamming code has been used. This is because we have found that most of the frames are hit by very few errors. The Hamming code redundancy bits occupy 1 byte (7 bits + a constant '0'). The 11 data bytes (plus one byte for the code redundancy bits) of the information field in the frame of Fig. 2 are partitioned as shown in Table III.

Name	**#bits**	**#bytes**
Local area address	8	1
Receiver address	8	1
Transmitter address	8	1
Control bits: 1. Receiver addr mode: Unique / Group 2. Acknowledge requested 3. Streaming 4. Acknowledge on request 5. – 8. Reserved for future purposes	8 1 1 1 1 4	1
Data	48	6
Checksum bits	8	1

Table III. Bit allocation within the frame of Fig. 2.

Local area address: This address defines the area which the unit belongs to. A unit shall in principle only communicate with units within the same local area, except for the Overall Identification Commands defined in the Net structure layer, which use the local area address 255. Valid addresses are in the range [1, 250]. The addresses 0 and 251 – 254 are reserved for future purposes

Receiver address: If the first control bit is equal to 1, this position contains the unique address of the receive node. If the first control bit is equal to 0, this position contains the group address of the nodes which the frame is meant for. Valid addresses are in the range [1, 250]. The address 0 is used for broadcasting. The addresses 251 – 255 are reserved for future purposes.

Transmitter address: This is the unique address of the transmitting node. Valid addresses are in the range [1, 250]. The addresses 251 – 255 are reserved for future purposes.

Control bit 1: Receiver address mode: unique/group: If this control bit is 1, the used receiver address relates to a unique address, else it relates to a group address.

Control bit 2: Acknowledge required: If this bit is 1, the receiver is requested to send an acknowledgement to the transmitter, telling that the frame is received and that the checksum is correct. This bit shall only be used if the Unique/group bit is 1, the used address differs from 0 (Broadcast), and the control bit 4 is equal to 0.

Control bit 3: If this bit is 1, this frame is a part of a stream.

Control bit 4: Acknowledge on request. This bit is 1 when a node sends an acknowledgement frame as a response on a frame with the acknowledge control bit set.

Control bit 5 to 8: These are reserved for future purposes.

Data: This field is 6 bytes long. It is used to either send commands in non-streaming mode (Command-ID, Command-data) or to stream data.

Checksum: The sum of all 11 bytes should be 0xFF (modulo 256), and the checksum byte is used as the remaining part of the sum of the other 10 bytes.

E. *Net Structure Layer*

The network structure, as seen from a node, is divided into two parts; the local area which the node is a member of, and the overall net (which might in turn consists of other local areas). This division is implemented to introduce logical segments separated by the use of a Local Area Address without necessarily using costly physical net filters. Within this layer a node identification service is defined and implemented during the configuration of a network, or when adding nodes to a network. The service consists of a set of commands that help to identify the address of units connected to the power line. The identification commands (request command and a response) have 2 levels, Internal Identification Commands (for identifying units within the same local area) and Overall Identification Commands (for identifying units in the neighborhood, both inside and outside the local area).

IV. WIRENET HARDWARE PROTOTYPE

To verify and test the proposed system, a WireNet Transceiver Unit (WTU) was developed (Fig. 4), consisting of the needed hardware and software. The modular structure of the WTU is depicted in Fig. 5.

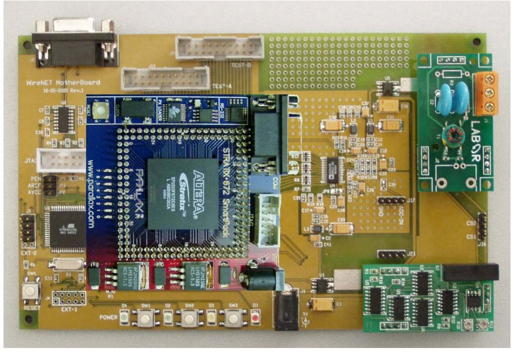

Fig. 4: Photo of the developed WireNet Module

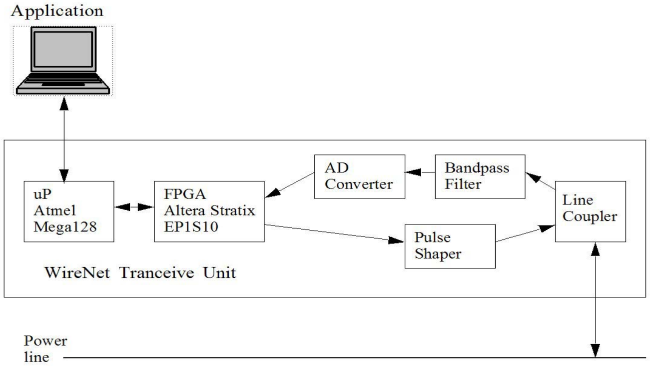

Fig. 5: Modular structure of the WireNet Transceiver Unit

The WTU is interfaced to the main power line via the line coupler. This balanced coupler has an approximately flat frequency response within the frequency range covered by the employed transmitting pulses. The received signals, from the power line via the line coupler, pass through a band pass filter. After filtering, the signals are analog-to-digital converted with a sampling rate of 50 MHz, into a 12 bit + overflow word. The digitized signal is fed into a Field Programmable Gate Array. The FPGA is clocked with a basic clock of 50 MHz. The FPGA monitors the power of the incoming signal. When the signal exceeds an adjustable trig level, the FPGA starts to seek for frame synchronization, i.e. to seek for the predefined Training Bits in the frame. When the sequence of Training Bits is found, the received signal signature is related to the expected ideal signature of the Training Bits. The difference, which represents the channel response, is then used to digitally implement the matched filter receiver. The detected Information Bits are then passed to the micro-processor (uP) that implements the channel decoder (in the prototype a Hamming code was used, only). Finally, the received frame is sent to the application via a RS232 line. Messages from the application are received in the uP via the RS232 line. The uP implements the Hamming coding, and send the Information Bits, to the FPGA, together with information about which WireNet equipment class (HRTC/SRTC/URTC) to use. The FPGA forms a raw frame and monitors the inter-frame time. When the appropriate inter-frame time is fulfilled, the FPGA clocks out the raw frame bits. Each bit is shaped by the pulse shaper and then sent via the line coupler into the power line. Although the serial line between the application and the WTU is rather slow (9600-38300 bit/s), the speed of the WireNet frames on the power line are much higher: 500 kbits/s for a raw frame.

V. DESCRIPTION OF TESTS

A number of tests have been carried out, as all project participants have designed their own test and focused on applications relevant for their area of interest.

A. General Line Transmitting Test

The general line transmitting tests have varied from long range transmitting of few control data with high demand for reliability, to streaming of sound and graphical pictures where the correctness were judged by human subjective observations. A general test mechanism has been implemented in the WireNet Transceiver Unit, to "standardize" and ease the test. The first subtest uses a back-to-back connection with 130 meter cable not connected to a power line. This test confirmed error free performance. The second subtest uses a setup as shown in Fig. 6, where the two WTUs are connected via a real power line. More PC power supplies, computers and a fluorescent lamp were connected.

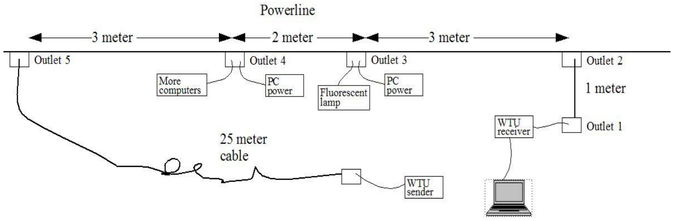

Fig. 6: Test setup for general line transmitting test, using real power line.

In total 14 x 100 messages (134400 bits) were sent. 1389 messages were fault free (99.2%), no message was lost, 9 messages had 1 bit error each, corrected by the Hamming code, and 2 messages had more than 1 bit error each. The third subtest uses the same setup as shown in Fig.6. In addition, one more switched power supply of poor quality was attached to outlet 3. In total 12 x 100 messages (115200 bits) were sent. 376 messages were fault free, 82 were lost, 410 messages were containing 1 bit error (corrected by the Hamming code) and 332 messages had more than 1 bit error.

B. *Analysis of the Noise*

A key point in the WireNet concept is the use of a ultra wide band transmit pulse with most of the energy in the range above 1 MHz. Empirically, the continuous electrical conducted noise in this frequency range is low, whatever considering light industry, office buildings or home installations. Momentarily, however, some electrical equipment can emit conducted noise during switching on and off. To verify this empirical knowledge, a number of measurements were carried out in (light) industry scenarios, as this category was expected to be the toughest concerning electrical conducted noise. As a reference, we consider the noise spectrum on a line that is directly connecting two WTU. See Fig. 7.A. A typical noise spectrum measured in the field on a 230V line is shown in Fig.7.B. To see the expected transient effect of a “noisy” equipment, the spectrum was measured on the power line close to the connection of a fluorescent lamp, while the lamp was continuously switched on and off, see Fig.7.C, which shows a number of spikes on the spectrum. As shown by the figures, the measurements confirm that the back ground noise on a power line is quite low in the focused frequency range. Transient noise from equipment might, however, be annoyingly high and may occasionally trig the receiver of a WTU even if the signal trig level is set to the maximum.

C. *WireNet Transmitting through Different Phases*

The WireNet concept has been tested in the following net configuration: Single phase net, Three phase IT net (L1, L2, L3), Three phase TN net (L1, L2, L3, N). The conclusion of these tests is that the received power drops more significantly when going from one phase to another in an IT or a TN net, compared to transmitting on a single phase net with equivalent load (electrical equipment) connected. The reduction of power is measured in up to 50%, and thus it is less serious than the reduction caused by connecting high capacitive equipment on the net. The transmitting error rate is equivalent on all the measured net configurations.

D. *Conclusion Summary of the Tests*

The tests indicate that for many applications the WireNet concept has a good error rate and quality performance. The stationary background noise does not have as much influence as the impulsive noise. The system works well on three phase grids. Loading the power line with high capacitive equipment will reduce the received power of signal, and therefore it may reduce the coverage distance.

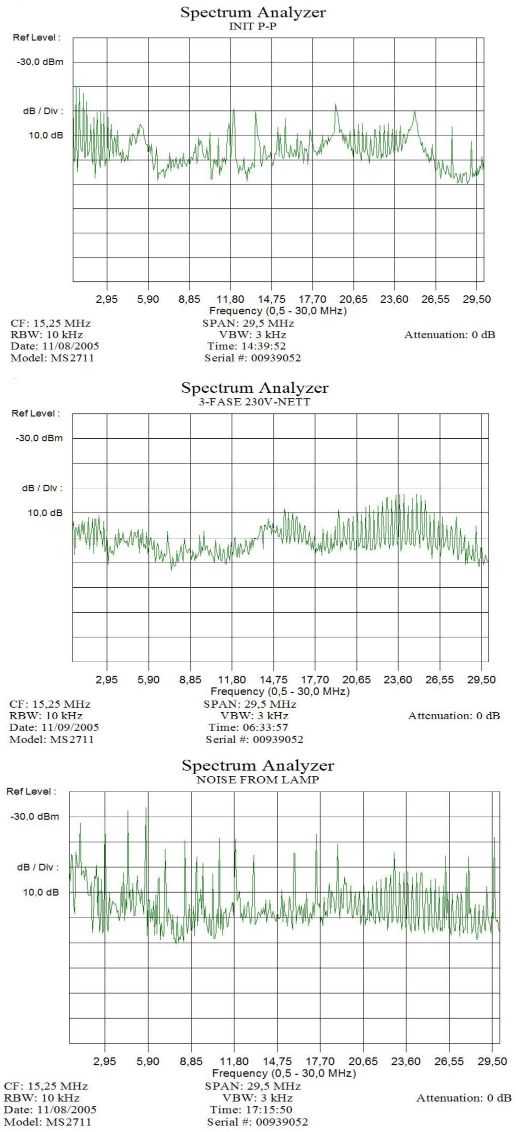

Fig.7: The spectrum of:

A) Background noise on a line directly connecting two WTUs back to back.

B) Background noise on a 230V power line.

C) Background noise while switching on and off a fluorescent lamp.

VI. CONCLUSIONS

We have described an experimental system for indoor PLC based on wide band impulse modulation. The current hardware WireNet prototype provides good performance. Improvements are expected with improved error correction codes, higher level modulation, receiver algorithms [3]. Some work on this is going on, and in particular several aspect as industrialization and market deployment are under consideration.

REFERENCES

[1] M. Win, R. Scholtz, "Impulse radio: how it works", *IEEE Comm. Letters*, vol. 2, pp. 10-12, January 1998.

[2] A. Tonello, R. Rinaldo, M. Bellin, "Synchronization and channel estimation for wide band impulse modulation over power line channels", Proc. of *ISPLC 2004*, Zaragoza, Spain, pp. 206-211, March 2004.

[3] A. Tonello, “An impulse modulation based PLC system with frequency domain receiver processing”, Proc. of *ISPLC 2005*, Vancouver, pp.241-245, April 2005.

[4] M. Zimmermann, K. Dostert, "A multipath model for the powerline channel", *IEEE Trans. on Comm.*, vol. 50, pp. 553-559, April 2002.

[5] CENELEC EN55022 “Information technology equipment – Radio disturbance characteristics – Limits and methods of measurement”.

[6] CISPR 16-1 “Specification for radio disturbance and immunity measuring apparatus and methods – Part 1”.