Abstract — This work describes the functionality of the "User Environment Area Network" (UEAN) and explores some issues related to its practical implementation. An UEAN is a network that connects the electronic devices that belong to a person, in spite of their physical location. The "Functional Convergence" (FC) of personal electronic devices allows the implementation of virtual personal electronic devices, that are implemented by grouping sources, sinks, storage, processors or gateways that belong to the UEAN. We explore the feasibility to use water copper pipelines as the backbone to establish a UEAN based on the interconnection of several Wireless Personal Area Networks (WPAN) operating in the different rooms of a house. The copper pipeline represents a good candidate to interconnect the multiple WPAN because of its high bandwidth and strong shielding to external electromagnetic noise. Some measurements in the 2.4 GHz frequency band are presented. The converging trends observed in telecommunications technology and markets, make us believe that it is important to study and model a network of personal devices in terms of an UEAN.

Index Terms — UEAN, Functional Convergence, WPAN, cooper pipes communications.

I. INTRODUCTION

The need and availability of complex personal communication services (involving voice, data, video, etc.), anywhere and anytime, has been rapidly growing for the past 20 years.

The quest to provide improved services, has lead to the emergence of different communications networks to address the different needs of information exchange at the corporate, home or office, and personal level. The favored solution is to establish the connectivity between two nodes using a hierarchical arrange of networks according to the distance that separate the nodes. In this sense, a personal area network (PAN) has been defined as the network that connects a person's device within his personal space [1].

The effort to provide improved services, has also lead the telecommunications industry to the Communications Convergence (CC). In a broad sense, the CC trends are dramatically changing services, technology, markets, business models, and regulation. High expectations exist around the fact that CC would make possible for a single device to perform the triple play.

In this work we consider a different kind of convergence; one in which every device will serve to a unique function, and will work within a network of personal environment range, connecting with other devices of such network (despite their physical location) to provide a specific service to the user. We call it Functional Convergence (FC).

In this paper we also consider a different kind of personal network; in which the electronic devices and gadgets of an individual (or a group of individuals) interconnect with each other and work together, within the boundaries of the user's environment (e.g., home or office), not limited by proximity restrictions (like a Bluetooth PAN). We call this a User Environment Area Network (UEAN) [2], and we illustrate one possible implementation using the water pipelines inside a home [3].

The UEAN type of networks, along with the Functional Nodes, can bring to reality interesting cross-functional interactions and applications. However, the needs of information exchange demand good electromagnetic shielding, high capacity of data transfer, and a suite of applications and protocols running on top the network connecting the devices.

The copper pipelines within a house represent a viable and attractive infrastructure to connect the multiple WPAN of the home UEAN, because they can be used as conducting waveguides to transport large amounts of data with perfect shielding from outside electromagnetic noise.

In the next sections we discuss more details about FC, UEAN and explore some issues related to its implementation.
II. FUNCTIONAL CONVERGENCE

In a typical home we can find a television set composed of a display, a set of speakers, a TV processor and a TV gateway (cable or satellite connection). At the same time, we might find a computer composed of a display, a set of speakers, a CPU processor, memory, and a network gateway (DSL or cable modem). There could also be one or many cell phones, as well as a land-line phone, DVD player, sound system, radio and many other personal electronic devices. It turns out that in such a typical home we can count several displays, speakers, microphones, memories, processors and gateways; each of which are inconveniently attached to their respective devices, so they are restricted to work with such devices only (e.g. the speaker in the cell phone can only be used with the cell phone, but not with the TV set or the computer).

In a modern communications era, the components of an electronic personal device do not have to be physically attached and constrained by such ties to limit its functionality. Thus, within the scope of a functional convergence framework, every display within the network could be available to work with any set of other devices to serve its purpose as an interface to the user (i.e., watch TV, view the photos from a digital camera, work with a PC, and monitor a surveillance camera).

In general, the functional nodes will be classified as: source, sink, memory, processor or gateway, and they will be interconnected through a person's UEAN.

III. USER ENVIRONMENT AREA NETWORK (UEAN)

The UEAN is the base for connectivity among the multiple functional devices that belong to an individual's environment (such as the home or the office), and work together as a single virtual electronic device that provides a service to the user. Since the functional nodes are not attached to each other, they can disconnect from one group functional nodes that work as a virtual electronic device, and get connected to a different group (within the UEAN) whenever the user needs it. This kind of network can bring to reality interesting cross-functional interactions, and applications.

Traditionally, we think of a communications network in terms of its coverage: Personal Area Network (PAN), Local Area Network (LAN), and so on [4]. The UEAN, however, considers the coverage of a network in a different perspective, because it connects all the electronic devices in the environment of the user, without interfering or being interfered by neighboring networks. The UEAN coverage is NOT defined in terms of a distance or a line of sight, but in terms of the devices that belong to the user and need to be interconnected.

As depicted in figure 1, one possible structure of a UEAN consists of several WPANs that are confined to closed spaces, but interconnected through a wired and/or wireless LAN. This structure allows interconnecting all the devices that belong to a user (despite their physical location).

Within a short range, the UEAN is nothing but a typical wireless PAN (e.g. Bluetooth); so the components within a closed space interact with each other, without the use of wires and in a smart way. However, in a longer range, the UEAN accounts for a wired or guided (shielded from external interference) connection of all the WPANs that exist within the user's environment; thus covering all the devices that belong to a user, whether they are in the same closed space or not, with no interference to other UEANs in the neighborhood.

To make FC happen we need a suite of applications and protocols running on top the network, to connect the devices that belong to it.

A. Relevant emerging technologies

The telecommunications industry is currently going through revolutionary transformation process, where technologies are changing rapidly to converge and provide a completely new generation of communications services. As we have stated before, we believe that the trends of convergence are leading into the Functional Nodes and the User Environment Area Networks. In the following subsections we briefly review some of the most important trends of the industry.

B. WPANs, WLANs and WMANs

Today, the communications networks establish connectivity between two nodes using a hierarchical arrange of networks, according to the distance that separate the nodes: PAN, LAN, MAN, and so on (see figure 2). In this kind of architectures, there are several alternatives for each level of hierarchy. For example, in wireless communications we can use WiMax for the access to the Metropolitan Area Network, WiFi for the Local Area Network, and Bluetooth for the Personal Area Network [5]. As mentioned before, these networks enable the UEAN connectivity; however, they need a suite of applications to handle the Functional Convergence.

C. Ad-Hoc Networks

An ad-hoc networks account for wireless nodes with the capability of self configuration, that together form a communication network without the aid of a predetermined infrastructure or central control [6]. Just like a PAN/LAN architecture, Ad-Hoc networks enable the establishment of the UEAN, at the physical and MAC layers; however, they

Fig. 2. Hierarchy of networks.
need a suite of applications to handle the Functional Convergence (that is, to allow the coordinated interaction of functional modes, to establish virtual electronic devices).

D. Peer-to-Peer
A peer-to-peer (or P2P) network relies primarily on the computing power and bandwidth of the participants in the network, rather than concentrating it in a relatively low number of servers. P2P networks are typically used for connecting nodes via largely ad hoc connections. These networks are useful for many purposes, like sharing content files containing audio, video, data or anything in digital format, and real-time data, such as telephony traffic [7]. A UEAN may work as a P2P network, or not, because there may be one or few servers that bring the computer power and control the interconnection of the functional nodes.

E. Software Defined Radio (SDR)
A software-defined radio system is a radio communication system which uses software to implement the functions of modulation and demodulation of radio signals; with the goal of having a radio that can receive and transmit a new form of radio protocol just by running new software. The Software Defined Radio allows a group of permanently attached nodes to perform as different devices [8]; however, the SDR differs with the UEAN concept because UEAN does not require the nodes to be attached, and in fact the nodes are permanently detached to perform as any virtual device.

F. 4G
4G is a wireless access technology that aims to be the successor of 3G [9]. 4G would provide users with mobile, on demand high quality video and audio. The 4G wireless access technology, as well as WiMax and other mobile broadband access technologies, support the establishment of UEANs, as they give them mobile access to external networks.

IV. IMPLEMENTATION ISSUES
In order to implement the UEAN we need to couple the multiple WPANs that exist within the user's environment. The WPANs are connected in a way that the connection is shielded from the outside noise, and has a large capacity for data transfer. Such connection turns out to be very simple, because it can be achieved with several wired or wireless "bridges" (one in each of the WPANs).

The "bridges" are simple repeaters that direct signals in and out the wires that interconnect them, giving the impression that all the WPANs conform only one single network, one that fits perfectly the users environment, but does not interfere (or is interfered) by external electromagnetic (EM) noise.

For example, at home one can use the electric supply wiring, or the copper pipelines for water distribution [3] as the backbone to interconnect the WPANs that exist in the different rooms, thus establishing the desired UEAN. This kind of infrastructure is viable and attractive to make the connections, because it can transport enormous amounts of data with a perfect shielding from outside electromagnetic noise.

The UEAN type of networks can bring to reality interesting cross-functional interactions and applications. However, the needs of information exchange demand (among other things): extremely high capacity of data transfer and good interference shielding.

![Fig. 3. Architecture of the UEAN based on copper pipelines.](image)

V. A UEAN BASED ON WATER COOPER PIPELINES
In this section we analyze the possibility of using the copper pipelines within a home, as the backbone to interconnect multiple WPAN located in different rooms. The UEAN based on cooper pipelines is depicted in figure 3.

A. Coupling to the Copper Pipeline
The copper pipelines within a house represent a viable and attractive infrastructure to connect the multiple WPAN of the home UEAN, because they can be used as conducting waveguides to transport large amounts of data with perfect shielding from outside electromagnetic noise.

![Fig. 4. A coupler for UEAN.](image)
connects without the need of wires to the WPAN in the room, and buffers any signal in and out the pipeline.

The device uses simple dipoles to achieve the coupling: a simple dipole is used to radiate and receive the signals into the room (just like any commercial wireless modem), and a dipole inserted half way into the pipe line, is used to extract/supply the signal into it. Since the carrier frequency inside the pipeline may be different from the 2.4 GHz frequency band of a Bluetooth network, the coupling system requires up/down frequency converters; as well as amplifiers.

B. Conducting pipeline characterization

Once the signal is buffered into the copper pipeline, it travels through it subject to propagation effects (such as attenuation). To understand the wave propagation through the copper pipeline, and its implications to the establishment of a UEAN, we look at the pipeline as a long (several wavelengths) circular hollow metallic wave guide, and model it starting from the Maxwell equations for free space (i.e., there are no charge and/or current inside the pipeline) [10]:

\[ \nabla \times E + \frac{\partial \mathbf{B}}{\partial t} = 0 \]  \hspace{1cm} (1)
\[ \nabla \times B - \frac{1}{c^2} \frac{\partial E}{\partial t} = 0 \]  \hspace{1cm} (2)
\[ \varepsilon_0 \nabla \cdot E = 0 \]  \hspace{1cm} (3)
\[ \nabla \times B = 0 \]  \hspace{1cm} (4)

These equations reduce to the wave-equation given by:

\[ \nabla^2 E - \mu \varepsilon_0 \frac{\partial^2 E}{\partial t^2} = 0 \]  \hspace{1cm} (5)

For analysis purposes, all possible particular solutions are separated into two orthogonal components: TE (the electric field has no \( \hat{z} \) component) and TM (the magnetic field has no \( \hat{z} \) component).

Each particular solution inside the wave guide, can be understood as a combination of simple harmonic waves that satisfy the wave equation (5) and propagate along the waveguide as they bounce off it's walls. Each of these simple harmonic waves propagate along it's wave vector: \( \mathbf{k} = \hat{k}_r + \hat{k}_\theta \); which satisfies the dispersion relation: \( |\mathbf{k}| = \omega \sqrt{\mu \varepsilon} \). Therefore, the propagation constant (along the waveguide) is given by:

\[ k_z = \sqrt{\omega^2 \mu \varepsilon_0 - k_r^2} \]  \hspace{1cm} (6)

For a given frequency (\( \omega \)), and considering the reference frame illustrated in figure 5, the resulting fields show simple propagation in the \( \hat{z} \) direction, with a stationary pattern (envelope) along the pipeline cross section \((r, \phi)\):

\[ \mathbf{E}(r) = \mathbf{E}(x, y) e^{-jk_z z}. \]  \hspace{1cm} (7)

To find the stationary pattern for the TM modes, and thus understand their propagation characteristics, we separate the stationary envelope into longitudinal and transverse components:

\[ \mathbf{E}(x, y) = E_r(x, y) + \hat{z} E_z(x, y) ; \]  \hspace{1cm} (8)

and find (from the wave equation) an equation for the \( \hat{z} \) component of the electric field:

\[ (\nabla^2 - k_z^2 + \omega^2 \mu \varepsilon) E_z(r, \phi) = 0 \]  \hspace{1cm} (9)

where:

\[ \nabla^2 = \frac{\partial^2}{\partial r^2} + (1/r) \frac{\partial}{\partial r} + (1/r^2) \frac{\partial^2}{\partial \phi^2} \]  \hspace{1cm} (10)

Equation (9) is already written in terms of cylindrical coordinates, and in the frequency domain (i.e., complex electric fields). This is solved by the separation of variables method, assuming that \( E_z(r, \phi) = F(\phi)R(r) \). The general homogeneous solution is:

\[ F(\phi) = A \cos(\nu \theta) + B \sin(\nu \theta) \]  \hspace{1cm} (11)
\[ R(r) = CJ_{\nu}(kr) + DN_{\nu}(kr) \]  \hspace{1cm} (12)

where \( J_{\nu} \) and \( N_{\nu} \) are Bessel functions of the first and second kind, of order \( \nu \). The arbitrary constants \( A, B, C, \) and \( D \), need to be evaluated by considering the boundary conditions at the inner metallic walls of the wave guide.

Considering that \( N_{\nu}(kr) \) has a singularity when its argument is zero (the center of the pipe line), \( D = 0 \) is necessary for a meaningful solution.

Evaluating boundary conditions at the metallic surface of the waveguide (\( E_z = E_\phi = 0 \), when \( r = a \)) implies that \( J_{\nu}(kr_a) = 0 \); which allows multiple solutions for each value of \( \nu \) and the number of zeros \( n \) between the center of the pipeline and the boundary. All the possible solutions are named after \( \nu \) and \( n \), as \( TM_{\nu, n} \). If \( \xi_{\nu, n} \) is the \( n_{th} \) root of the \( \nu_{th} \) order Bessel function, then \( k_r = \xi_{\nu, n} / a \).

Without going any further, we round up our analysis by looking at the cut-off frequency of the \( TM_{\nu, n} \) mode (\( \omega_{\nu, n} \)).
below which the mode cannot propagate through the pipeline. Since 
\( k_z = \sqrt{\omega^2 \mu \varepsilon - k_r^2} \), the propagation constant \( k_z \) is
real only when \( k_r^2 > \omega^2 \mu \varepsilon \); which implies that the cut-off
frequency is:

\[
w_{c, r} = \frac{1}{\mu \varepsilon} \sqrt{\frac{\varepsilon_{r,u,n}}{a}}.
\] (13)

When \( \omega < \omega_{c, r} \), the propagation constant \( k_z \) is pure
imaginary, so the wave attenuates as it propagates into the
pipeline.

A similar analysis, which we skip for brevity reasons, gives
us the cut-off frequency for the \( TE_{0,1} \) mode:

\[
w_{c, 0,1} = \frac{1}{\mu \varepsilon} \sqrt{\frac{\varepsilon_{r,u,n}}{a}}.
\] (14)

where \( \varepsilon_{r,u,n} \) denotes the roots of the first derivative of the
Bessel Function of the first kind: \( J_1' \). This is: \( J_1' \left( \varepsilon_{r,u,n} \right) = 0 \).

The cut-off frequencies of the different modes define the
range of frequencies that can be used to transport information
through the pipeline. For the scopes of this paper, this
information is enough to demonstrate that the pipeline is a
suitable medium for the interconnection of WPAN that exist at
home.

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**C. Propagation and attenuation effects**

Propagation effects (such as attenuation and dispersion) are
the crucial elements to be considered before going deeper into
implementation analysis. To analyze such effects, we begin
defining the range of carrier frequencies that can be used for
the communication along the pipeline.

For optimal transmission (i.e. reduce dispersion effects), the
carrier frequency needs to be selected so the signals can only
propagate in one single mode of propagation; that is, the
carrier frequency needs to be above the lowest cut-off wave
guide frequency, and below the cut-off frequency of all the
other modes.

The mode with the lowest cut-off frequency (the Principal
Mode) is the \( TE_{11} \). Considering that the water inside the
pipeline has a relative permittivity \( \varepsilon_r = 77 \) (an average
between the distillate and sea water permittivity), the cut-off
frequency for the principal mode is (see (14)):

\[
w_{c, 11} = \frac{c}{\sqrt{\varepsilon_r}} \frac{\varepsilon_{11}}{a} = \frac{c}{\sqrt{77}} \frac{1.8412}{a}.
\] (15)

The next lowest frequency corresponds to the \( TM_{01} \) mode
(see (13)):

\[
w_{c, 01} = \frac{c}{\sqrt{\varepsilon_r}} \frac{\varepsilon_{01}}{a} = \frac{c}{\sqrt{77}} \frac{2.4048}{a}.
\] (16)

The optimal carrier frequency, \( \omega_{TE11} < \omega < \varepsilon_{TM01} \), for
typical pipeline diameters of 1/4, 1/2 and 1 inches, are shown
in Table 1.

As it can be observed, even the thicker pipelines (1 inch
diameter) supports a carrier frequency of 5.5 -6.6 GHz, which is
high enough to transport signals with the 802.11a standard. The
complete range of frequencies 5 to 25 GHz can be handled with
technology that is commercially available nowadays.

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**Table 1. Cut-off frequencies (in GHz).**

<table>
<thead>
<tr>
<th>Diameter</th>
<th>( \omega_{TE11} )</th>
<th>( \omega_{TM01} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4 inch</td>
<td>29.1</td>
<td>26.3</td>
</tr>
<tr>
<td>1/2 inch</td>
<td>10.1</td>
<td>13.2</td>
</tr>
<tr>
<td>1.0 inch</td>
<td>5.0</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Attenuation along the pipeline occurs because the
waveguide is not filled with a perfect dielectric material; but
with water, which is a conducting material with conductivity
\( 10^{-4} < \sigma < 5 \). This means that the signal may suffer a
strong attenuation along its path through the pipeline. To
evaluate the implications of water’s conductivity, we first
evaluate the loss tangent (LT), considering a \( \omega = 10 \) GHz and
a permittivity \( \varepsilon = 77 \varepsilon_0 \): \( LT = \sigma / \omega \varepsilon < 0.7 \). Given
the small LT, we consider the water as a bad dielectric and
approximate the penetration depth \( \delta \) as [10]:

\[
\delta \approx \frac{2 \varepsilon}{\sigma \mu}.
\] (17)
For a conductivity $10^{-4} < \sigma < 5$, we find that the penetration depth is $0.01 < \delta < 466$ m; which means that the signal inside the pipeline would attenuate in a factor of $1/e$ as it travels a distance between 1 cm and 466 m. Even if this calculation is not accurate enough (it needs to be refined considering the actual conductivity of the water inside the pipeline), it shows us that the attenuation is not a real problem. As negative as this may sound, the waveguide is completely shielded, so we can supply as much power as we need. In such case, the attenuation is a positive effect, because it cleans out spurious echoes that can result from the multiple paths that the signal follows inside the pipeline.

VI. SOME EXPERIMENTAL RESULTS

In this experiment we measure the bandwidth of a wave wide to confirm that a signal in the 2.4 GHz band can indeed be transmitted in a metal pipe. Figure 6 shows a description of the experiment and depicts the actual experimental setup. The waveform generator is the HP 8648C and the spectrum analyzer is the HP 8592L.

The metallic waveguide has a diameter of about 3 inches, with a cutoff frequency $\omega_{fe11} = 2.37571$ GHz. The pipe has one metallic lid at each extreme. The distance between a dipole and the closest lid is $\lambda/2$. The distance between dipoles is $2.5 \lambda$. Each dipole must have a length equal to $\lambda/8$, as depicted in figure 7.

Table 1 also shows the results of the measurements, showing a maximum received power at 2.469 GHz, with a 10 dB bandwidth spanning from about 2.450 GHz to 2.750 GHz.
Table I. Table showing results from measurements.

<table>
<thead>
<tr>
<th>Freq. (MHz)</th>
<th>Rx Power (dBm)</th>
<th>Rx Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2100</td>
<td>-65.8</td>
<td>2.63027E-07</td>
</tr>
<tr>
<td>2150</td>
<td>-51.6</td>
<td>6.9105E-06</td>
</tr>
<tr>
<td>2200</td>
<td>-43.9</td>
<td>4.079E-05</td>
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<tr>
<td>2250</td>
<td>-29.9</td>
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<td>2300</td>
<td>-20.1</td>
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<td>2350</td>
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<td>2400</td>
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<td>2490</td>
<td>6.3</td>
<td>4.26795118</td>
</tr>
<tr>
<td>2500</td>
<td>3.8</td>
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<tr>
<td>2800</td>
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<td>0.288293552</td>
</tr>
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<td>2850</td>
<td>2.3</td>
<td>1.690214652</td>
</tr>
<tr>
<td>2900</td>
<td>0.3</td>
<td>1.071519305</td>
</tr>
</tbody>
</table>

VII. DISCUSSION AND CONCLUSION

This work describes the functions of the User Environment Area Network, considering a Functional Convergence; and analyzes some issues of their implementation. These kind of networks, combined with the Functional Convergence framework, states a new way to understand the establishment of a network, one that encompasses all the devices that belong to an individual and allows a hole new spectrum of applications.

Throughout this paper we have reviewed the wave guide theory for the circular metallic hollow wave guide; and used such theory to analyze the range of frequencies and attenuation effects that would be relevant, if the home pipelines were to be used as the backbone to interconnect different WPAN located at the different rooms of the house.

After proposing a device that could be used to direct information in and out the home pipelines, we found that the optimal carrier frequency to transport information through the home pipelines (0.25 to 1 in diameter) is 5 to 25 GHz. The optimal frequency range that was found, is relatively easy to handle with commercially available devices, and is high enough to support, for example, operation of Bluetooth devices, provided a connector with a mixer is used (see fig. 4).

We also came up with a rough estimate of the damping of the waves inside the pipeline, considering that they are filled with water. Such analysis demonstrated that even if attenuation exists, it is not so intense that it will annihilate the signals in the pipeline, within the range of lengths at home (1-30 m). The attenuation of the signal is not an issue, specially when we consider that the pipeline is completely shielded from outside environment, so we can use as much power as we desire to transmit through it. In any case, attenuation effects are positive because they clean out spurious echoes.

The range of frequencies and the estimated magnitude of the damping, are encouraging results that motivates us to continue our search. Considering the results obtained, we believe that it is possible to achieve a suitable transmission through the pipeline and will continue working to refine our model and start building a prototype to connect Bluetooth devices though a 1/2 inch diameter copper pipe.

Preliminary experimental results showed that it might be feasible to transmit signals in the 2.4 GHz band.

Even if not clearly stated anywhere else, we believe that the proposed kind of network is a viable future for communication between personal devices, and we believe some trends in the communications industry seem to point in that way. We further believe that any work related to the understanding and establishment of the UEAN networks and the Functional Nodes, will have a strong impact for personal device interconnection, in the near future.

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