Copper pipelines for high capacity communication between multiple WPAN, to establish a User Environment Area Network at home

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Abstract—This paper describes the work in progress towards understanding the feasibility to use a copper pipeline as the backbone to interconnect the Wireless Personal Area Networks (WPAN) that exist in the different rooms of a house, in order to establish a User Environment Area Network (UEAN). The UEAN can interconnect all the electronic devices of a user, within its personal environment, without interfering (or being interfered) by neighboring UEANs, allowing the exchange of information with multiple high bit-rate channels. With the establishment of a UEAN, all the electronic devices and gadgets at home can exchange voice, data, and video, in real time. The copper pipeline represents an excellent way to interconnect the multiple WPAN that are established within different rooms (bluetooth and WUSB technologies), because of its high bandwidth and strong shielding to external electromagnetic noise.

I. INTRODUCTION: USER ENVIRONMENT AREA NETWORKS

The need and availability of complex personal communication services have been rapidly growing for the past 20 years. Considering the actual trends of the telecommunications industry, sooner than later all the devices that belong to an individual will connect with each other, in a wireless and smart way, conforming networks that are transparent to the user. We call this networks User Environment Area Networks [1], because they connect all the devices within the boundaries of the user’s environment (e.g., home or office) without proximity or line of sight restrictions. The UEAN are able to trespass walls, but they do not interfere (or are interfered) by neighboring networks.

The basic structure of a UEAN is a wired network of Wireless Personal Area Networks (WPAN); as illustrated in Figure 1. In a short range, the UEAN is nothing but a typical WPAN (i.e., Bluetooth, WUSB, or a combination of them); so the components within a closed space interact with each other, without the use of wires. However, in a longer range, the UEAN accounts for a wired (shielded from external interference) connection of all the WPAN that exist within the user’s environment; thus covering all the devices that belong to a user, despite their physical location, without interfering other UEANs.

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. In the following sections, we analyze the possibility of using the copper pipelines within a home, as the backbone to interconnect multiple WPAN located in different rooms.

II. 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.

The device illustrated in Figure 2 can be used to couple the multiple signals inside a room (bluetooth or WUSB) into the copper pipeline. The proposed system is conceptually quite simple: it 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 2-10 GHz
characteristic of a bluetooth network, the coupling system requires up/down frequency converters; as well as amplifiers.

III. 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 waveguide, and model it starting from the Maxwell equations for free space (i.e., there are no charge and/or current inside the pipeline) [2]:

\[
\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0, \quad (1)
\]

\[
\nabla \times \mathbf{B} - \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t} = 0, \quad (2)
\]

\[
\epsilon_0 \nabla \cdot \mathbf{E} = 0, \quad (3)
\]

\[
\nabla \cdot \mathbf{B} = 0. \quad (4)
\]

These equations reduce to the wave-equation given by:

\[
(\nabla^2 + \mu \epsilon \frac{\partial^2}{\partial t^2}) \mathbf{E}(\mathbf{r}) = 0. \quad (5)
\]

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 (Eq. 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: \( \mathbf{k} = \mathbf{r} k_r + \hat{z} k_z \); which satisfies the dispersion relation: \( |\mathbf{k}|^2 = \nu^2 c^2 \). Therefore, the propagation constant (along the waveguide) is given by:

\[
k_z = \sqrt{\nu^2 \mu c - k_r^2}
\]

For a given frequency (\( \omega \)), and considering the reference frame illustrated in Figure 3, the resulting fields show simple propagation in the \( \hat{z} \) direction, with a stationary pattern (envelope) along the pipeline cross section \( (r, \phi) \):

\[
\mathbf{E}(\mathbf{r}) = \mathbf{E}(x, y) e^{-jk_z z}. \quad (6)
\]

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:

\[
\mathbf{E}(x, y) = \mathbf{E}_T(x, y) + \hat{z} \mathbf{E}_z(x, y); \quad (7)
\]

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

\[
(\nabla^2 r - k_z^2 + \omega^2 \mu c) \mathbf{E}_z(r, \phi) = 0; \quad (8)
\]

where: \( \nabla^2 r = \partial^2 / \partial r^2 + (1/r) \partial / \partial r + (1/r^2) \partial^2 / \partial \phi^2 \). Equation (8) 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:

\[
F(\phi) = A \cos \nu \phi + B \sin \nu \phi, \quad (9)
\]

\[
R(r) = C J_\nu(k_r r) + D N_\nu(k_r r); \quad (10)
\]

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 \( N_\nu(k_r r) \) 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 \( (E_z = E_\phi = 0, \text{ when } r = a) \) implies that \( J_\nu(k_r a) = 0; \) 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: \( \text{TM}_{\nu,n} \). If \( n_{\nu} \) is the \( n_{\nu} \) th root of the \( \nu_{\text{th}} \) 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 $TM_{r,n}$ mode ($\omega_{r,n}$), 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:

$$\omega_{r,n} = \sqrt{\frac{1}{\mu \varepsilon}} \xi_{r,n}. \quad (11)$$

When $\omega < \omega_{r,n}$, 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 $TE_{r,n}$ mode:

$$\omega_{r,n} = \sqrt{\frac{1}{\mu \varepsilon}} \xi_{r,n}'; \quad (12)$$

where $\xi_{r,n}'$ denotes the roots of the first derivative of the Bessel Function of the first kind: $J'_r$. This is: $J'_r(\xi_{r,n}) = 0$.

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.

IV. 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 permittivities), the cut off frequency for the principal mode is (see Eq. 12):

$$\omega_{11} = \frac{c}{\sqrt{\varepsilon_r}} \frac{\xi_{11}}{a} = \frac{c}{\sqrt{77}} \frac{1.8412}{a}. $$

The next lowest frequency corresponds to the $TM_{01}$ mode (see Eq. 11):

$$\omega_{01} = \frac{c}{\sqrt{\varepsilon_r}} \frac{\xi_{01}}{a} = \frac{c}{\sqrt{77}} \frac{2.4048}{a}. $$

The optimal carrier frequency, $\omega_{TE_{11}} < \omega < \omega_{TM_{01}}$, 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 $5.5 - 6.6 \text{ GHz}$, which is high enough to transport signals with the WUSB standard. The complete range of frequencies 5 to 25 GHz can be easily handled with technology that is commercially available nowadays.

<table>
<thead>
<tr>
<th>Diameter</th>
<th>$\omega_{TE_{11}}$</th>
<th>$\omega_{TM_{01}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4 inch</td>
<td>20.1</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>

**TABLE I**

**CUT OFF FREQUENCIES (IN GHz).**

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 $\omega = 10 \text{ GHz}$ 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 [2]:

$$\delta = \frac{2}{\sigma} \sqrt{\frac{\varepsilon}{\mu}}.$$  

For a conductivity $10^{-4} < \sigma < 5$, we find that the penetration depth is $0.01 < \delta < 466 \text{ m}$; 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.

V. DISCUSSION AND CONCLUSIONS

Through out 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 Bluetooth and WUSB standards.

We also came up with a rough estimate of the damping of the waves inside the pipe, 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 through a 1/2 inch diameter copper pipe.

VI. ACKNOWLEDGMENTS

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REFERENCES
