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EDUCATIONAL AND MATHEMATICAL PERFORMANCE OF WIRELESS COMMUNICATION USING WI-FI FOR DIFFERENT SCENARIOS

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Abstract- The impact of electromagnetic wave applications in the day-to-day life of most people is increasing during the last months. In this way, schools and universities are also applying more applications that work in a wireless mode. But education system has also a responsibility to teach this communication type and its basics and concepts, particularly in Engineering. Moreover, since 2020, with the pandemic due to COVID-19, the importance and also the notoriety of wireless communications, especially Wi-Fi, have become a trend topic. Online classes and teleworking require good and reliable methods of communication and data transmission. This has driven the development of the various technologies associated with electromagnetic waves. New application scenarios of the Internet of Things (IoT) have also been incorporated, with a great expansion in their use. Therefore, the practical performance of some of these technologies in concrete and potentially common usage scenarios is analysed, with an educational point of view for engineering degrees and with a mathematical development.

Keywords: Wireless Communication, Wi-Fi, Information Network, Information Transfer.

1. INTRODUCTION

The use of wireless technologies has been booming in recent years, largely due, among other factors, to their potential application in multiple fields and their ease of scalability [1-3]. At the University of the Basque Country, a comparative analysis project is being carried out of several of these technologies in personal area networks: RFID, NFC, Bluetooth, Wi-Fi and Zigbee.

Each of them has a series of advantages and disadvantages that make them more or less suitable [4, 5]. Consequently, choice of technology must depend on the requirements of particular application, and a compromise must be found between price, power consumption and the bandwidth it is capable of providing [6, 7].

These wireless technologies are one of the foundations for the communication of one or more computer networks [8]. We can say that a computer network is basically a set of systems that are connected to each other, that are able to send, receive and share information between them. They are pieces of equipment that together create such a network and allow, through transmission media and communication devices, the connection and sharing of data. They are also crucial to organise and prioritise the different connected elements, as well as to guarantee the integrity and security of the data (for example, by placing the servers with the databases in an area away from the local area network where the equipment works) [9, 10]. In the following section, some of the types of networks that exist are briefly discussed. The connection between the different computers (nodes) that make up the network can be made by cable or by using wireless technologies.

In this paper, we will focus on the study and results concerning Wi-Fi technology, developing also an educational and mathematical point of view.

2. TYPES OF NETWORKS

The term network refers to a set of independent computer systems connected to each other, with the aim of enabling data exchange, which requires both the physical and logical connection of the systems. The latter is established by means of special network protocols, such as TCP (Transmission Control Protocol).

Depending on the size and scope of the computer network, a differentiation can be made between different network dimensions. The most important of these are:

2.1. Wireless Body Area Network (BAN)

WBAN or BAN is a network where only low-power devices are connected to the body of a human being.

Devices that can work with this technology can be complex equipment such as a cellular phone or a simple component such as a headset or a visor fitted to glasses and typically communicate over distances of 1 or 2 metres (the connection does not exceed 5-8 metres before the devices begin to fail due to inefficiency). The most widespread use of this technology is in the field of health and healthcare, and these devices will be different depending on the target.

All messages coming from the sensors are collected by a network controller and processed by a personal server. Communication between the personal server and the Internet interface is carried out by using WLAN and WAN technologies.

2.2. Personal Area Networks (PAN)

These are networks capable of supporting segments of about 10 metres in length. A PAN is typically used to connect personal devices such as mobile phones, headsets and personal digital assistants to each other, to other stand-alone devices and to larger networks, without the need for cables. In this case it can be referred to as a uplink or uplink. Due to the limited range and relatively low data transmission rate, PANs are mainly used to connect peripherals in the entertainment sector. In the context of the Internet of Things (IoT), WPANs are used for the communication of control and monitoring applications with a low data rate. In this respect, protocols such as Insteon, Z-Wave and ZigBee have been specially designed for home automation and home automation.

2.3. Home Area Networks (HAN)

This type of network emerged due to the development of communication and interoperability between home electronic equipment. A HAN can include both equipment inside the home and equipment in the immediate vicinity of it.

Devices capable of using this network (smart devices such as laptops and network printers) usually achieve greater emerging capabilities through their ability to interact.

This usually implies an improvement in user benefits, as it normally involves a better use of the features that the equipment can offer (for example, automation of repetitive tasks) and even complementarity among the various connected equipment. Until a few years ago, the equipment operating within these HANs were computers and media players. However, mainly due to the cheapness of some electronic equipment and the simplicity of its handling (both for communication between equipment and for technical use), the capacity for operation and control of equipment and data has increased significantly, and it is possible to monitor and control many devices via an application on a smartphone.

2.4. Local Area Networks (LAN)

A LAN is a network that connects one or more computers within a limited space. Through a LAN, resources can be shared among several computers and computing devices, be it peripherals, information stored on the server or Internet access points.

This type of network is common in businesses and homes, and has a different topology according to the needs of the network:
- Bus network. The same cable connects the computers and allows data transmission in a straight line.
- Star network: All computers are connected to a central server that manages the network resources and allocates them as requested.
- Ring network. All computers are connected to their neighbours via a one-way transmission, which interrupts the network if there is a failure at any level of the network.
- Mixed network. Combines two or more of the above models.

Wireless Local Area Network (WLAN) is actually a LAN, which is not realised through wired connections. Instead, it uses wireless technology, through which individual computers communicate with each other or are connected to another network, such as the Internet. In this way, a WLAN can be connected as a LAN to a MAN network and through it to a wide area network.

2.5. Metropolitan Area Networks (MANs)

A MAN is a network that, through a high-speed connection, provides coverage over a large geographical area (such as a city). It is composed of CAN or LAN networks spread over a specific area. It has various applications, including the deployment of VoIP (Voice over Internet Protocol) services, thus allowing the elimination of traditional telephone lines. It is also used in municipal video surveillance systems, computer-to-computer interconnections, wide area network (WAN) gateways, etc.

2.6. Wide Area Networks (WANs)

WANs are large-scale networks spanning countries and even continents. They do not connect individual computers, but other networks such as LANs or MANs. WANs may be public or managed by companies to connect multiple locations over long distances.

These networks use a uniform addressing scheme because unaddressed forwarding of data would be inefficient with the number of networks connected. Intermediate systems or network nodes ensure that sent data packets are forwarded to the desired address.

2.7. Global Area Networks (GAN)

This is the global network of networks, i.e. the Internet. However, it is not a single connection, as companies with a presence in many countries also have their own network of servers.

3. STANDARDISATION AND PROTOCOLS

The IEEE 802 code is used to refer to the standards proposed by the committee of the same name, IEEE 802, which deals with computer networks, both LAN and MAN. The 802 network standard defines 22 categories.

In February 1980, a local networking committee was formed, with the aim of standardising the Ethernet of the time. It was decided to standardise at the physical level as well as at the link level and above. The physical level includes the transformations that are made to the sequence of bits to transmit them from one place to another. The link level refers to the transfer of information over a data transmission circuit. It therefore receives requests from the network layer and uses the services of the physical layer. The link layer was divided into two sub-layers:
- the logical link layer, which is responsible for forwarding logic, flow control and error checking, and
- the medium access sub-level, responsible for arbitrating conflicts of simultaneous access to the network by stations.

Finally, the scope of work was progressively extended to include metropolitan area networks (less than 100 km), regional area networks (more than 100 km) and personal area networks (a few metres). Wireless networks (WLANs), different security protocols and methods, etc. were also added.

In particular, IEEE 802.15 refers to the group specialised in wireless personal area networks (WPAN). This group allows portable devices (PCs, tablets, phones, sensors, ...) to communicate with each other. This wireless networking protocol is created to coexist with WLANs (802.11), because Bluetooth cannot. This standard was defined to allow the interoperability of wireless LANs with PAN or HAN networks.

4. WI-FI TECHNOLOGY

Wi-Fi is a technology that arose from the need to establish a way of wireless connection that was compatible with different devices. It is a trademark of the Wi-Fi Alliance, the organisation that was formed in 1999 to develop and enable standards for interoperability and compatibility with previous versions, and to drive forward wireless local area network technology [11, 12].

It consists of a wireless adapter that translates the data as a radio signal and transmits it, and a router that receives the signal, decodes it and via a physical connection (cable over Ethernet) sends the information over the Internet to other servers. This process is reversed when it is the client that has to receive the information from the Internet.

A Wi-Fi access point is an area with wireless connectivity that creates a wireless local area network (WLAN) to which we can connect from other devices.

In terms of security, it depends on the encryption that is applied to the communications between the router and the wireless adapters. The options are divided into secure and non-secure depending on their technical characteristics:

- WEP (Wired Equivalent Privacy): In 1999, it was the most widely used in the world, but its use has naturally decreased, and although the main flaws and holes have been solved, it is an unreliable encryption.
- WPA (Wi-Fi Protected Access): WPA was the answer to the main flaws and vulnerabilities of WEP. The keys used by WPA are 256 bits, as opposed to WEP's 128, and it incorporates content and integrity checking of messages to prevent them from being intercepted and the use of the TKIP temporary key protocol, which helps to prevent a router from being easily attacked as was the case with WEP.
- WPA2: The main difference with WPA is the use of AES, which performs block ciphering to allow for longer and more secure keys and the implementation of CCMP which is an enhanced encryption protocol that replaces TKIP.
- WPA3: Incorporates 192-bit encryption instead of 129-bit encryption, which makes the encryption more secure. This makes it more secure even with weaker passwords, so the same key is more vulnerable to brute force attacks in WPA2 than in WPA3.

The purpose of the 802.11 standards was to develop a communication layer for local wireless connectivity for fixed and mobile devices.

The IEEE 802.11 standard provides an asynchronous and time-limited connection, and also supports service continuity in multiple areas through a distribution system.

- 802.11a: Works with connections up to 54Mbps, operates in the 5GHz band.
- 802.11b: Connections up to 11Mbps, operates in the 2.4GHz band.
- 802.11g: Connections up to 54Mbps, operates in the 2.4GHz band.
- 802.11n: Connections up to 600mbps, operates in the 2.4GHz and 5GHz band.
- 802.11ac: Connections up to 1300Mbps, operates in the 5GHZ band.

5. WI-FI: CALCULATING LOSSES

RF waves transmitted by Wi-Fi wireless networks are attenuated and interfered by various obstacles and noise. In an unobstructed space, the propagation loss can be calculated with the following equation (1):

$$L_p = 92.4 + 20 \cdot \log_{10}(d_{km}) + 20 \cdot \log_{10}(f_{GHz}) \quad (1)$$

The frequency value depends on the channel on which the equipment is configured.

For calculating losses due to various obstacles, we can make use of the Egli model [13,14], which calculates a quick approximation:

$$L = G_t \cdot G_r \cdot \left(\frac{h_t \cdot h_r}{d^2} \right)^2 \cdot \left(\frac{40}{f} \right)^2 \quad (2)$$

Normally, the total losses are usually determined in the various studies by the losses due to diffraction [15,16]. Apparently, an obstacle may not cause diffraction in the signal, but it is necessary to analyze the Fresnel zones to be able to reach a conclusion. A Fresnel zone is the volume of space between the emitter of a wave -electromagnetic, acoustic, etc.- and a receiver, such that the phase difference of the waves in this volume does not exceed 180º. If the obstacle is within the first Fresnel zone, diffraction losses can generally be significant.

Fresnel zones are calculated using the following equation (3):

$$R_n = \sqrt{\frac{n \cdot \lambda \cdot d_1 \cdot d_2}{d}} \quad (3)$$

where:

r_n = radius of the Fresnel zone (n = 1, 2, 3 ...).

d_1 = distance from the transmitter to the center of the ellipsoid in meters.

d_2 = distance from the center of the ellipsoid to the receiver in meters.

λ = wavelength of the transmitted signal in meters.

$d = d_1 + d_2$

The first zone being the most important. Applying the equation (4), we obtain the radius of the first Fresnel zone (r_1 of the previous formula), knowing the distance between two antennas and the frequency at which they transmit the signal, assuming the object located at the center point:

$$R_1(m) = 8.656\sqrt{\frac{d(km)}{f(GHz)}} \quad (4)$$

where:
r_1 = radius of the first Fresnel zone, in meters.
d = distance in kilometers ($d_1 = d_2$, $d = d_1 + d_2$).
f = transmission frequency in gigahertz (GHz) $(\lambda = c / f)$.

If we assume that several objects are located at different places from the central point, we must apply the following equation (5) to obtain the radius of the first Fresnel zone, knowing the distance between two antennas and the frequency at which they transmit the signal:

$$R_1(m) = 17.32\sqrt{\frac{d_1(km)\cdot d_2(km)}{f(GHz)\cdot d(km)}} \quad (5)$$

where:
r_1 = radius of the first Fresnel zone, in meters.
d_1 = distance from the transmitter to the center of the ellipsoid in kilometers.
d_2 = distance from the center of the ellipsoid to the receiver in kilometers.
d = distance in kilometers ($d = d_1 + d_2$).
f = transmission frequency in gigahertz (GHz).

The shape of the obstacle inside the first Fresnel zone must also be taken into account, and there are two usual cases: if the obstacle is sharp and isolated, or if it is rounded.

In the case of a sharp and isolated obstacle, the losses take the following equation (6):

$$L_D(\nu) = 6.9 + 20\cdot\log_{10}\left(\sqrt{(\nu-0.1)^2+1}+\nu-0.1\right) \quad (6)$$

On the other hand, if the obstacle is rounded, a correction is applied with respect to the acute obstacle, adding extra losses depending on the curvature of the obstacle (*r*), its width and the angle it forms with the straight paths to the antennas:

$$L_{extra} = 11.7\times\alpha\times\sqrt{\frac{\pi r}{\lambda}} \quad (7)$$

$$r = \frac{2d_s\cdot d_1\cdot d_2}{\alpha(d_1^2+d_2^2)} \quad (8)$$

In Wi-Fi wireless networks, transmission speeds decrease as we move away from the Wireless Access Point. This is, obviously, due to the distance and to the fact that walls (or obstacles) and transmissions from other equipment attenuate the signal. Therefore, the transmission speed of a wireless Wi-Fi network will be a function of distance, obstacles and interference.

6. WI-FI PERFORMANCE TESTS: METHODOLOGY

Performance tests have been carried out on this technology in four scenarios with different physical conditions that affect the quality of the link. The tests have also been divided to analyse performance in the transfer of large files in small numbers, transfer of small files with a high number of files and a real-time application, having chosen VoIP telephone calls for this case.

6.1. Test Catalogue

The tests to be carried out using Wi-Fi technology have been divided into 3 sections:
- Transfer of small files.
- Transfer of large files.
- Real-time application.

6.2. Small File Transfer

It has been proposed to transfer files of 3 different sizes (approximate, as powers of 10 are used): 500 B, 1.5 KB and 10 MB. A large number of files will be transferred in inverse proportion to their size. Files of 10 MB are also included, although these would be considered more of an average size, but since the large test will only work with very large files, it has been considered appropriate.

A script has been built in which we will generate files with random content in base64, and given that prior to the time control tests additional tests are carried out, the number of files to be generated of each size has been parameterised to minimise the time. A time stamp has also been taken during the execution of this script for information purposes.

6.3. Large Size Transfer

Similar to the previous point, 1 GB and 3 GB files will be generated on the server. In this case, both in terms of size and time, the number of files will be reduced.

6.4. Real-Time Application

The idea was to make voice calls (VoIP) between two computers. The initial idea was to make use of a public Internet service where clients could register and make these calls. In order not to affect the tests due to uncontrolled effects on Internet access or the provider's service, this initial idea was rejected and a complete scenario was built in the local environment.

We propose making calls lasting approximately 1 minute, capturing the traffic produced so that it can later be analysed. The subjective assessment of the quality of the call is also taken into account, albeit in a lateral way.

The real time tests will be carried out taking into account the same conditions taken into account for the file transfer tests. In this case, additionally, two types of calls will be used, in order to obtain results with a SIP client installed on a PC and a SIP client installed on an Android mobile device. Therefore, they will be:
- PC - PC VoIP call
- PC - PC VoIP call - mobile device

6.5. Conditionalities

Once we have defined the elements that we cannot change, the performance will be affected mainly by the variable of signal loss due to distance and by the intermediate elements between transmitter and receiver. Therefore, two different types of tests are performed:
- The tests are performed considering that the server is connected by cable (there is no effect except on the client side).
- The following scenarios with described conditions (Wi-Fi physical conditions) are considered:

1. Minimum and free distance to router (< 1 m).
2. Medium and free distance to router (< 15 m).
3. Short distance with one separation obstacle (< 5 m).
4. Medium distance with different level and 2 separating obstacles (< 15 m).

A test with 2 levels of difference is started, but it is cancelled due to the lack of signal. Another variable to take into account, depending on the space in which it operates, is loss of performance due to sharing use of radio space.

Connection and traffic conditions, that is, Wi-Fi shared environment constraints, are the following:

1. Server connected by cable and traffic in the whole network exclusively for the tests.
2. Server connected by Wi-Fi and additional traffic generation (not affecting server).

The traffic generated will use additional machines with file transfer, TV and mobile content streaming (YouTube, Netflix, ...).

The tests carried out are identified with the matrix generated with the two conditions, as we can see in Figure 1, where some tests are shown, corresponding to large size files and exclusive traffic for the communication.

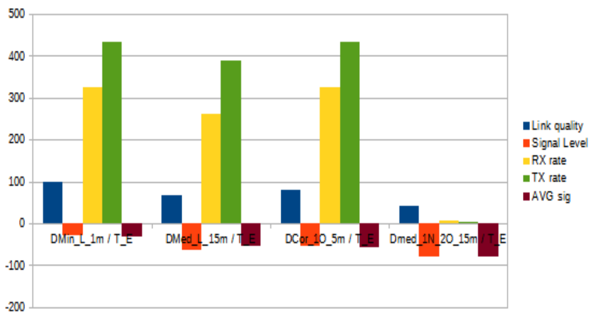

Figure 1. Large files, Exclusive traffic

7. WI-FI PERFORMANCE TESTS: ANALYSIS AND DISCUSSION

As indicated in the object of this work, no comparisons are made in relation to the theoretical data set out in the standards. In this sense, the comparison is limited to what a priori could have been considered the most optimal situation, and as the tests are transferred to more unfavourable scenarios, both in terms of distance and traffic circumstances, the differences obtained can be assessed.

7.1. Physical Constraints

The reports obtained at the link level present a situation that is in principle foreseen, but not completely. Although in the situation where the equipment is at a minimum distance of less than 1 metre, the quality of the link is reported as 100%, and the signal values and transmission and reception ratios are high, the distance penalty (15 m) is greater than in the scenario where an intermediate obstacle appears (approximately 10%). Considering the theoretical distances achievable with this technology, a lower penalty would have been expected.

It is also necessary to take into account that the obstacle considered in the third scenario is an internal wall of a house, which obviously subtracts a considerable percentage of signal (approximately 20%), but allows a very high quality level to be maintained.

The fourth scenario, already more forced, presents very reduced quality values (< 50%), and a signal level close to -80 dB, which is already close to the acceptable limits. The transmission and reception ratios have also suffered a very significant reduction.

It can be seen that the power level reported by the monitor does not vary in any of the four scenarios, i.e., at least under the conditions tested, no adaptation of any kind takes place.

Regarding the shared traffic, it should be noted at the outset that in the tests carried out for the chosen location (isolated), it was not necessary to carry out an initial spectrum analysis monitoring analysis to see the occupation of channels and the possible impact of other deployed networks.

Likewise, the traffic that it has been possible to generate has been limited to 8 devices, all of them running Internet streaming services (movies and YouTube videos):

- 2 TVs
- 2 PCs
- 2 Tablets
- 2 Smartphones

Under these circumstances, no penalties were observed on the monitoring equipment. The values have been the same, with the only differences being the time of printing of the monitor report, which fluctuates continuously but with minimal variations.

7.2. Transfer Rate and Time Spent

In the data obtained in these tests, some aspects of interest have been found:

- The theoretically optimal scenario, where the equipment is located at short distances and where the link quality and signal values have been the highest, has not reported the best values in any case.
- Scenarios 2 and 3, which had differentials of about 10% at the link level, reported the highest values and behaved very similarly. However, scenario 2 without obstacles, where the most penalised at the link level, outperformed scenario 3 in terms of performance.
- The most unfavourable scenario has already obtained highly penalised performance values. It practically halves the transmission rate by doubling time spent on the tasks.

Regarding the shared traffic, in the comparisons made in each scenario with shared traffic, it can be seen that the differences have been very low (< 10%), and even in scenario 3, the best values have been obtained with shared traffic.

8. CONCLUSIONS

In recent years, the development of telecommunications has been oriented towards the intensive use of broadband systems with high levels of quality, through the development of high transmission capacity technologies, among which we can highlight fibre optics to the subscriber's home. Cable-based systems are generally expensive to install and are difficult to build, install and commission. In addition to this, the development of these means of transmission in rural areas and areas of preferential social interest represent investments that are very difficult to recover due to the characteristics of the demand.

Faced with this situation and other technological and topographical limitations, wireless alternatives have been sought that allow for rapid deployment of the infrastructure, greater predictability in the amortization of the investment in the places where they are installed, as well as lower operating and maintenance costs.

Within this environment, Wi-Fi wireless standards, among others, have been developed. Wi-Fi was designed for indoor wireless environments as an alternative to structured wired networks and with a non-line-of-sight capacity of only a few meters.

From the tests carried out, it can be seen that Wi-Fi technology has allowed, both in circumstances that could be described as normal and also somewhat forced, the transmission of high volume and high number files with absolute correctness. It is important to point out that in addition to the tests reported, previous tests have been carried out in each of them, using different numbers of files and different volumes in order to adapt the tests to reasonable times, and in all of them the transfers have been completed without errors.

Scenario 4 identified should be considered as quite forced, and yes, in this case we have observed a very high penalty.

As indicated in the sub-section 4.5, there was a scenario 5, where it was proposed to include one more level (2 levels of difference), and in this case the signal was not sufficient in terms of power or stability, which in a certain sense is also a guarantee from the point of view of network security.

It is clear that there are other aspects to be taken into account (type of task to be carried out, specific conditions, reading time on the server, writing time on the client, additional tasks in progress on the machines, etc.) that will be at a higher level in the analysis of its performance.

In addition, the developed material can be very valuable for teaching and learning wireless communications, their analysis and design, as well as their mathematical basis.

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