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ANTENNAS FROM NON-CONVENTIONAL MATERIALS
ANTÉNY Z NETRADIČNÍCH MATERIÁLŮ

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AUTHOR David Sedlák
AUTOR PRÁCE

SUPERVISOR Mgr. Petra Langerová
VEDOUCÍ PRÁCE

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[1] SCARPELLO, M.L.; KAZANI, I.; HERTLEER, C.; ROGIER, H.; VANDE GINSTE, D. Stability and efficiency of screen-printed wearable and washable antennas, IEEE Antennas and Wireless Propagation Letters, 2012, vol. 11, p. 838-841. DOI: 10.1109/LAWP.2012.2207941

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Vedoucí práce: Mgr. Petra Langerová

Konzultant bakalářské práce: prof. Dr. Ing. Zbyněk Raida

doc. PhDr. Milena Krhutová, Ph.D., *předseda oborové rady*

Abstract

Production of alternative types of antennas is a very interesting sector of electro industry, and many of the world's largest companies but mainly portable electronical devices producers are involved in. However, the development as in any industries is in process. All of the process described in this thesis is verified and tested. It has to be noted that there are many more procedures and processes which are not described in this thesis. Therefore, the thesis will deal with: Antenna types for wearable application, wire antennas, aperture antennas, conductive material coating, screen printing, inkjet printing, implementation of conductive fibre into textile, printed glass antenna and practical realization of the aperture antenna.

Keywords

Wearable Antennas, Patch Antenna, Aperture Antennas, Conductive Coating, Conductive Fiber, E-textiles

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Introduction

Since ancient Egyptians were shocked of and fascinated by electric fish three thousand years before Christ and started discovering the world of electricity till the invention of battery a lot of time passed. Even more remarkable is the jump that was made from 1900 until these days in the field of electronic devices. All devices are faster, smaller, lighter, more portable, more durable and better than ever. People want to live in motion, and hence, there is a great need for wearable devices such as smartphones, smartwatches and bracelets, pressure-meters, speed meters, pulse meters and much more. Therefore, it is no surprise that big companies are involved in. For example, the first portable battery-operated reel-to-reel tape recorders were introduced in the 1950s. They were listened to with small loudspeakers, and they were too big to keep them in a pocket. Later in the 1960s, Panasonic introduced a small personal portable cassette player which was listened to with a headphones. The madness about wearable electronic started exactly at that time and continues till these days.

Radio, camera, phone, fax, mail, internet browser, fingerprints scanner – all of these features can be built in inside only one small portable device. The technology research and development of wearable components and devices goes forward and almost every day a new gadget comes out. In brief, a portable device usually consists of the following components: main-board (where central chip controls operations), a device for inputting commands (for example keyboard, touch-screen, etc.) and display (where we can clearly see how the portable device works). But there is another essential component which has to be mentioned - antenna.

Antenna is a modified part of the electric circuit. It serves as a receiver and transmitter of an electromagnetic signal. The size and shape of an antenna have to resonate with the transceiver signals. Therefore, main types, conductive coating, conductive printing, screen printing and glass printed antenna will be discussed in this bachelor´s thesis.

1. Electromagnetic waves

To understand the issue of wearable antennas it is necessary to formulate a brief introduction to the history of electromagnetic waves at the beginning of this bachelor´s thesis. The history and formation of electromagnetic waves will be described in this part. After that, the graphical representation of electromagnetic waves will subsequently be shown.

The existence of electromagnetic radiation was theoretically predicted and described by English physicist and chemist Michael Faraday in 1831. Michael Faraday was researching atmospheric procedures and phenomena, in particular, lightning. He wanted to know what cycles and procedures caused that phenomenon. While he was conducting his research he happened to discover electromagnetic waves. Nevertheless, Faraday's theory was only based on observation and experiments. The first person to mathematically describe the existence of electromagnetic waves thirty-two years later in 1865 was Scottish physicist and mathematician James Clerk Maxwell. He described the course of magnetic field lines in the vicinity of an electric power line and thus arrived at the vector differential equation. This differential equation states that every single power line generates an eddy current magnetic field. This revelation advanced current knowledge of electrical engineering tremendously.

James Clerk Maxwell showed mathematically that every single electric charge which is moving with non-zero velocity generates an electromagnetic field around a given conductor. Electromagnetic waves are propagated directly in all directions in an ideal environment. However, several factors affect the propagation of electromagnetic waves in the real conditions. These include reflections, noise, land surface roughness, etc. These factors must be taken into account in the design and, of course, in the construction of a transmitter or a receiver.

The movement of an electric charge in a conductor generates an electromagnetic field around the conductor which has two major components. The first major component is the electric field and the second component is the magnetic field. The E vector represents the electric field, and the H vector represents the magnetic field. Both vectors E and H are vectors of intensity and are perpendicular to one another.

See Figure 1. , where x, y and z are the axis; H is the magnetic field vector; E is the electric field vector, and c is the speed of light in vacuum, where c= 3×10^{8} m×s^{-1}. [1]

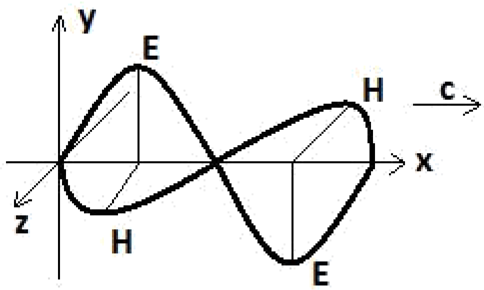

FIGURE 1. ELMAG. WAVE 1

2. Electromagnetic waves receiving

The first steps toward wireless communication were taken with the invention of the Branly's coherer by French inventor Édouard Branly around 1890. Branly's coherer was simply the first radio (electromagnetic) wave detector. The coherer (Figure B.) consisted of iron filings in an insulated tube between two electrodes. Electric resistivity rapidly decreases, and the iron filings can conduct an electric current in the presence of an electromagnetic signal. Édouard Branly found out how to increase the sensitivity of captured electromagnetic waves. That was a remarkable discovery, considering that technology at that time only allowed electromagnetic waves to be captured within a few meters.

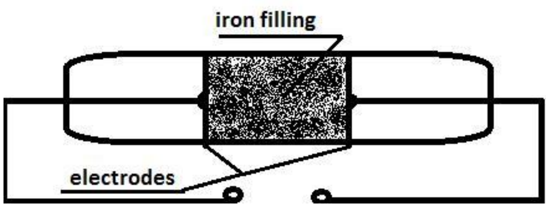

FIGURE 2. COHERER 1

The italian inventor and electrical engineer Guglielmo Marconi upgraded Branly's coherer and presented his radio communication experiment in 1898. He successfully made his first radio transmission between a boat and the mainland. However, the greatest boom in wireless communication technology came during World War I, World War II, and subsequently after 1958 when Jack Kilby invented the first integrated circuit. The age of miniaturization had begun. Every electronic device has since become smaller. Integrated circuits (IC) quickly replaced outdated and less efficient vacuum tubes. [2]

In 1973, Martin Cooper, an American engineer and visionary in the radio and wireless communication, invented the first handheld mobile phone at the Motorola Company, which was derived from a built-in car phone. In 1978, Motorola introduced the first commercially produced handheld mobile phone which was called Dynatac.[3] However, Dynatac was only a cordless mobile phone with a fixed station that was connected to a landline; hence movement with this device was also very limited.[4]

The very first cellular mobile phone system was launched into commercial operation in the Japan in 1979. This mobile network, the principle of which is still in use, can be imagined as a honeycomb. Each cell of the honeycomb is covered by a transmitter that also partially overlaps into adjacent cells. This cellular system ensures complete coverage of the desired area. Several cell sites were created around the world; mainly in the Scandinavian countries, England, France, and Germany. The problem was that cellular sites operated on different frequencies and mobile devices could not be used abroad. The main issue though was economic, specifically the market restriction for each type of device. This problem was solved by The European Conference of Postal and Telecommunications Administrations (CEPT) in 1982 when it established a new standardization group, GSM, which was tasked with developing standards for a new digital system that would be able to operate in countries across the world.[5]

The development and emergence of cellular networks around the world have meant a huge expansion of mobile devices and applications. Before 1990, portable mobile devices were only available for the army or a small group of people with high social status. After 1990, portable devices became more affordable and gradually spread among the general public. [6]

However, another network evolved in parallel with GSM. In 1960, the US Navy launched its satellite-based navigation system. This system served as a navigation tool for ships. The Global Positioning System (GPS), as was the system named, was made available to the general public in 1983. The world's first commercial handheld system was presented in 1983.All these technologies use electromagnetic waves for communicating with other devices or with bases and stations. The transmission and reception of signals can be interfered with by several factors (stochastic disturbance, parasitic signal, reflections, noise, land surface roughness, etc.).

3. Antenna systems for wearable applications

Therefore, the antenna is crucial for receiving electromagnetic waves as described in the previous paragraphs. The input signal amplifier of a device may be powerful, but without an antenna receiver, the values of the received signal are weak or imperceptible. The shape and placement of the antenna are also very important parameters. The shape of the antenna has to correspond with the electrical and mechanical requirements of the application. At the same time, the motion of the user should not be impeded by a wearable application. The antenna location also must meet a certain criteria.

The placement of a wearable antenna on the shoulders of rescuers is an excellent example. The team leader will be able to identify persons even in poor weather conditions or poor visibility. That will be possible because of cooperation between a visual system (for example smart glasses) and a radio system. Information about the person will be displayed in real time, and the observer will have a complete overview of desired information. The wearable device will be able to transmit information over long distances, even through walls. Measurements of pressure, temperature, and a pulse could be provided. This application could also be associated with different types of sensors- humidity sensor or sensors of explosive gasses. In the event of any unsafe conditions, this device could warn its user, or warn others.

As previously stated, antenna systems for wearable electronics can be conveniently integrated into clothes. There are two main approaches. Firstly, an antenna system can be installed directly on the surface of a garment. However, this method is more for disposable applications and not economically feasible. The repair or replacement of the antenna in case of failure is more expensive than a new antenna. Secondly, a wearable antenna system can be placed on a garment using a Velcro fastener. Such an antenna system can easily and quickly be disengaged and replaced in the event of failure.

Great demands are placed on mechanical resistance to the bending, tearing, and creasing which occurs during normal garment use. Other factors such as the presence of humidity or direct exposure to a stream of water must be taken into account. In addition to mechanical properties, the system must also have suitable electrical properties. While bending, the antenna should not change the level of received signal, or lose the signal. As this is a very young technology that has developed over a short period, it is clear that many new techniques will be put into practice in the next few years.

4. Antenna types for wearable applications

In this chapter, the antenna types that are convenient for wearable applications will be discussed in detail. The two main types of antennas for wearable applications are wire antennas and aperture antennas.

4.1 Wire antennas

Wire antennas are based on the principle of electromagnetic radiation emitted from a single wire or a system of conductors. The typical characteristic of a wire antenna is that it is much longer in length than in diameter. Single wires (Fig. 3.1), loops (Fig. 3.2), helical antennas (Fig. 3.3) or a combination thereof are the most commonly used antennas in wearable applications. [7]

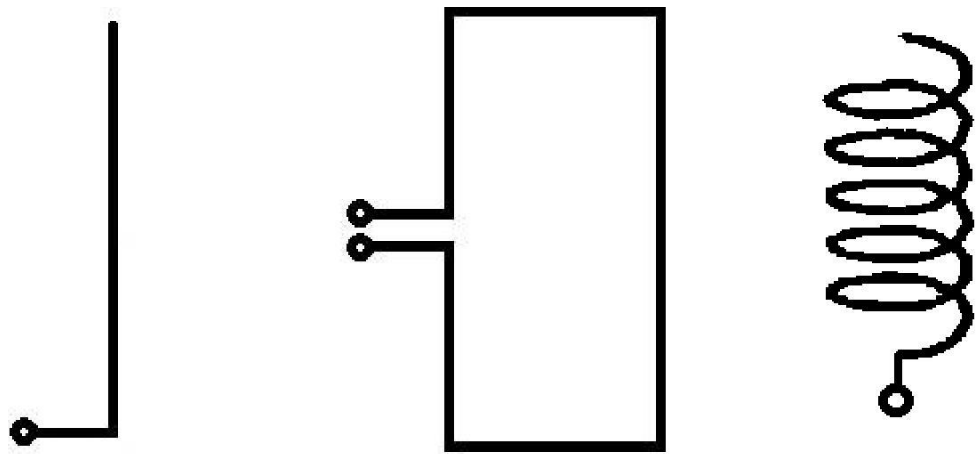

FIG 3.1, 3.2, 3.3 1

The wire antenna is the most basic and simplest antenna of all. It can be used for receiving in the horizontal position as well as in the vertical position – this depends on the application. Its other major advantages are low production cost and very simple production technology. This kind of antenna can be produced by simply etching a printed circuit on a flexible plastic plate which is lightweight and highly resistant to mechanical damage, or by using a specially modified wire. However, the biggest disadvantage, compared to other antennas, is the relatively small gain. The dimensions of a wire antenna and its directivity are determined by the antenna system application requirements.

For instance, a single wire antenna can be used as a transmitting and receiving antenna (transceiver) for Wi-Fi communication. Use of a wire Wi-Fi antenna is entirely dependent on the conditions at the place of operation. Short rod antennas designed for the 1/4 or 5/8 wavelengths are mostly commonly used commercially. These antennas are primarily omnidirectional, and their gain is dependent on the signal strength in a given location.

4.2 Aperture antennas

Commercial aperture antennas are especially used as strictly directive antennas with waveguides. Aperture antenna radiation is caused by currents flowing in the vicinity of the aperture. The antenna can have different shapes, and its shape has to be precisely constructed on its purpose. Therefore, its operation range is wide, but common working frequencies are from tens to hundreds of gigahertz. The disadvantage of the aperture antenna is the higher price compared to wire antennas. Nonetheless, this disadvantage is compensated by higher gain and smaller dimensions, which can be obtained with commercially available technologies.

Aperture antennas are used as omnidirectional antennas in wearable applications, where is not possible to place any waveguides. Adapters of the portable devices tend to have a planar inverted antenna that is etched directly onto a printed circuit board. These planar antennas began to be used during the development of perspective systems in modern high-capacity radio communications. They began to be used for data transmission because of their immunity to interference, security against eavesdropping and low power demands. These antennas are widely used in GPS modules (Global Positioning System) where they serve as a receiver and in GSM modules (Global System for Mobile communications) where they serve as a receiver and also as a transmitter. An aperture antenna is shown in Figure 4.

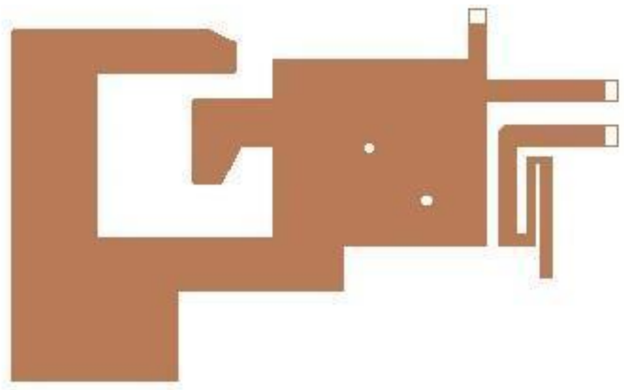

FIGURE 4: APERTURE MOBILE ANTENNA 1

Electronic monitoring of people via wearable electronic devices was developed in the early 1960s. The person who had committed an offense was sentenced to house arrest and had to wear a bracelet. This device worked on a simple principle. A stationary receiver was located in the given house, and the offender wore an electronic bracelet with the transmitter on a leg. If the offender moved beyond a given range, the police were notified. This device worked more or less on the same principle as RFID chips, which protect goods in a shop against thieves. The transmitter sent a signal to a receiver on the offender’s leg (where a small slot antenna was connected to an integrated circuit) and from there the signal was returned to the transmitter. The time it took the signal to travel was measured, and the distance from the transmitter was calculated. This principle was passive without feedback, and its use was limited. However, the rise of GPS technology has opened up new opportunities in this sector. A GPS bracelet that can be connected to a mobile phone application has almost unlimited possibilities. It is an active wearable technology that can be monitored anywhere in the world. A GPS receiver has the highest level of the gain when in direct visual line with a GPS satellite. However, the signal can also be detected from reflections and hence there are possibilities for an antenna system using a high gain aperture antenna.[8],[9]

5. Conductive material coating and wearable antenna requirements

There are many production procedures how to develop wearable antenna system. To place printed antennas on different surfaces for wearable communication is necessary to abide certain electrical and mechanical requirements for the use of the wearable antenna system. Wearable antennas have to be washable, bendable, durable, et cetera. Another specification that has to be taken into account is the fact that the human body absorbs a considerable portion of the electromagnetic wave radiated from the antenna. When new wearable antennas are developed for commercial use, the antennas have to be tested and complied with the regulations and limits of the International Commission on Non-Ionizing Radiation and Protection. The most common production procedures of wearable antennas will be explained in this chapter.

5.1 Screen printing

Screen printing belongs among one of the most widely used techniques for depositing or applying electrically conductive material onto a textile. It is depositing of conductive ink layer onto the textile substrate through the permeable mesh with a specific density of screen holes. The precision of antenna manufacturing and its final design is directly proportional to the density of mesh – so-called “screen internal width” and to dimension accuracy of holes in the mesh. Different methods significantly differ from each other only in the manufacturing of required mesh. Final mesh product for screen printing process is called mask.

The mask precisely determinates layout of predesigned pattern area for antenna screen printing onto textile substrate or fabric. The main advantage is relatively low production costs of this manufacturing process, and also possibility of wide range patterns deposition on a wide range of substrates including substrates with the porous and flexible surface. Therefore, screen printing can be used for printing on wood, paper, cork and of course onto textile substrates.

The most used screen printing process is depicted in the Figure ... and following steps are executed during the production process:

1. Step: Firstly, the base substrate is placed on the suitable frame. Thus its whole surface has to be perfectly flat and carefully taut without any surface deformations.
2. Step: The layer of photosensitive emulsion is deposited on the mesh side which will not be in the direct contact with the substrate base. This process is executed in the dark room only in the presence of the light source which is not emitting any light from the ultraviolet spectrum. This procedure is processed under similar light conditions like in procedures of threading a photo-film with photosensitive chemicals. Therefore, the red light is used as the light source because red light is on the opposite side of the light spectrum than violet light. At this point, the mesh is not in direct contact with the substrate, and is placed vertically in special frame – "screen frame". The back side is tightly pressed to some non-adhesive smooth surface (for instance made of plastic) meanwhile, the photosensitive emulsion is applied by a flexible squeegee into the mesh holes. The direction of application is always from bottom to top to prevent changes in emulsion thickness and emulsion dripping. In fact, the emulsion might drip if the viscosity of the photosensitive emulsion is too low. In this case, thorough washing or changing of the mesh and trimming of the screen frame tilt angle are necessary for the successful application. This step cannot be done precisely while the surface of the mesh is not smooth and defect-free.
3. Step: The mesh with currently applied emulsion is placed in the dark

environment for approximately six hours to ensure partial curing of the photosensitive emulsion. In the next step, the surface of the mesh with photosensitive emulsion has to be exposed to the ultraviolet (UV) light in the next forty-eight hours because the emulsion starts to lose declared chemical and mechanical qualities after this time.

4. Step: The positive pattern of the antenna is fabricated in this step. It has to be made from a lightproof material, which has to be placed in proportional position before the mesh. The illumination around its edges has to be perfectly covered. The required dimmensions of the antenna design have to be followed. Thus the transillumination is not acceptable in this step because of possible disruption of the photosensitive emulsion. The mesh with deposited emulsion is exposed to the light for a specific interval. The interval depends on thickness of the cured emulsion, thickness of the mesh, and on the power of the UV lamp. These specifications are always written in the emulsion datasheets. The power of the commercially produced UV lamps is up to 7000 W, of course, there are also lamps with higher or lower power.[10]
5. Step: After the exposure to UV light mesh is washed with a clean water of the temperature around 20°C until the unexposed layer of emulsion is not completely washed out. Nexth, the mesh is thoroughly dried and prepared to use.
6. Step: Mesh is tightly pressed to prepared frame from Step 1. and fixed directly to the screen frame. Accidental displacement of the frame with substrate and screen frame has to be avoided; otherwise successful depositing of conductive ink cannot be guaranteed. This set is fixed in horizontal position, and adequate amount of conductive ink is placed in the corner of the screen frame.
7. Step: The conductive ink is spread over the entire surface with elastic squeegee made of rubber. The conductive ink passed through the holes in the mesh, where is not the photosensitive emulsion cured, to the textile substrate. Finally, the antenna pattern is precisely printed.
8. Step: Screen frame with the mesh is unfixed and carefully removed

from its position; however the substrate textile with printed pattern of antenna remains in horizontal position. Removing of screen frame with mesh has to be done immediately after screen printing process. Otherwise, conductive ink can begin curing, and that can cause damage to the printed antenna pattern or damage of the mesh. Screen printed pattern is furthermore cured by heating, exposing to light, or the antenna is simply cured horizontally without any other steps.

Finally, the conductive ink curing process is usually done after approximately forty-eight hours. Nevertheless, the mesh and screen frame have to be washed, cleaned, deprived of leftover ink and dried immediately after screen printing operation. Also, if the mesh is cleaned and stored properly, it can be used several times for another screen printing operation with the same antenna pattern.

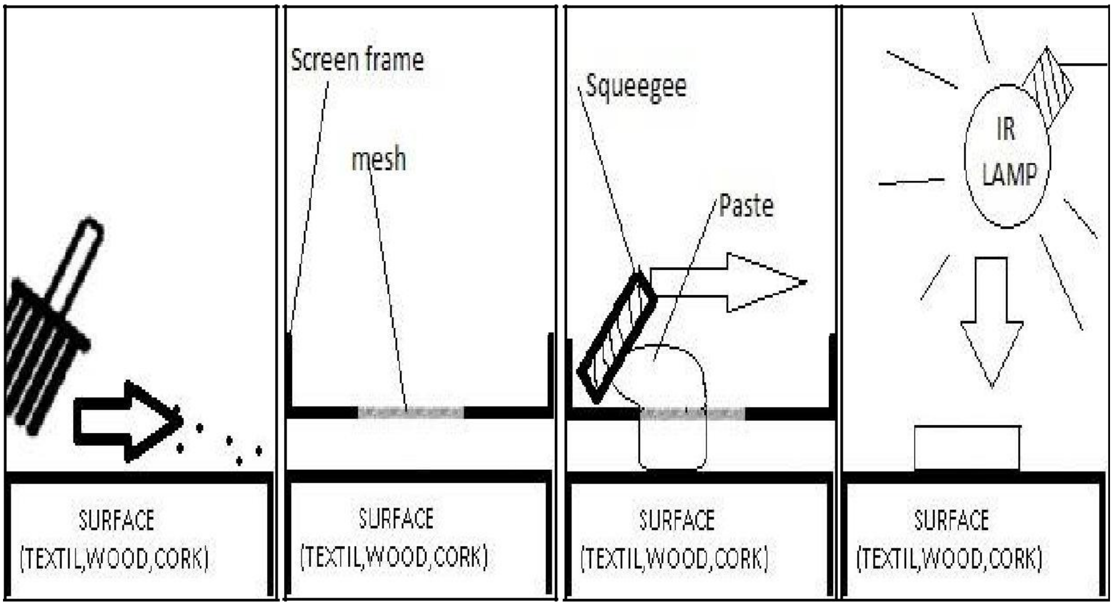

FIGURE 5. SCREEN PRINTING 1

There are many more screen printing processes which differ only in single steps. For instance, there are application possibilities of blocking lacquers, aliphatic materials, and liquid blocking solutions, instead of the photosensitive emulsion. Many of these liquids or solids are based on the principle of water repulsion. In principle, water repulsion material is applied on the back side of the mesh as a positive pattern; in the next step some water based blocking lacquer is applied. The water repulsion material gets into holes in mesh according to positive pattern design and water based blocking lacquer get into free holes in the mesh where it will be cured. Finally, the water repulsion material is washed, and leftover blocking lacquer serves as an antenna pattern. Thus, this method is not suitable for repeated use and is suitable only for small series production. There are many similar variations of these production operations; however, they are practiced only in a small series production. [11]

5.2 Electrically conductive ink

The electrically conductive ink, so-called "conductive ink", has to fulfill adequate mechanical and electrical characteristics of the antenna system. The conductive ink consists of two main components.

The first component is the hardening part of conductive ink. The hardening part provides tight connection among every single conductive element and conductive microelement. The hardening part determines the viscosity of the conductive ink compounded together with the thinners or solvents and with the second main component: conductive elements and conductive microelements. The Viscosity is an important parameter, which depends on the inner friction of the liquids and electromagnetic and magnetic attraction of every single particle in the conductive ink. The viscosity is usually denoted by Greek letter mu (μ), which is equivalent to pascal-second units (Pa·s) or kg/(m·s). [12] The viscosity parameter of the conductive ink is mainly important when is applied to textile or fabrication. The conductive ink might flow through the surface of the textile if the viscosity of the conductive ink is too low. and antenna system can be short-circuited under the textile surface. On the other hand, a wrong mechanical connection or issues in conductive ink boundaries can be caused by too high viscosity. Meanwhile the screen frame and mesh are removed the issues can appear, mainly due to the low connection ability. Another important parameter is the surface tension of the conductive ink. The surface tensions of the conductive ink together with viscosity parameters represent the uniformity ratio of the conductive ink. The surface tension is given by the Greek symbol gamma (γ), which is equivalent to Newton per meter (N/m) determined by the capillary behavior of the liquid material.[13],[14] Electrically conductive particles are the second main component of the conductive ink. Mass and size of particles have to be chosen properly with respect to parameters of the hardening component. Another essential parameter of the conductive ink is electrical conductivity, which is directly proportional to the electrical conductivity of the material of which are particles and microelements made. The electrical Conductivity, which is given by the ability of electric current to pass through the resistor, is denoted by letter G and its unit is siemens (S). Every single material has different electrical conductivity, thus, electrically conductive parts of the conductive ink are based on highly electrically conductive materials with free valence electrons such as copper (Cu), gold (Au), silver (Ag), aluminum (Al), their alloys, and other electrically conductive alloys. Although gold has one of the best electrical conductivity, its initial price is high. Therefore, the cost-effectiveness has to be taken into account, mainly in mass production. In this case, thoroughly considering of suitable materials is crucial. Conductive inks based on silver or silver alloys are the most suitable and widely used for conductive coating mainly due to their electrically and mechanically stable properties. Market with inks based on silver has been increasing during last few years causing the drop in the initial cost of these fabricating systems and applications. In contrast, silver based ink is not as oxidable as conductive inks based on copper. Due to this fact, the usage of silver-based inks is widely enhanced. [15]

Some of the conductive inks need to be exposed to a high temperature to complete its curing process and reach required mechanical and electrical properties. The product is inserted into a furnace, or the pattern is ironed after the conductive ink application. However, high temperature can damage inner structure or crystalline lattice of base material, which caused deformation of the whole product. Notwithstanding, there are many options how to cure conductive ink without exposure to a high temperature. The best solution is self-drying conductive inks. The main advantage is an initial cost, however on the other hand, in the curing process has to be waited for at least four hours. Another fast and cost effective curing process is photonic curing, which was developed by American company Novacentrix. Photonic curing is process, where photons are emitted from the photon source directly onto cured surface for only a few microseconds. Photons develop high temperature at the point of impact (only on the surface). This method is mainly suitable for curing of conductive layers deposited on synthetic materials, paper, or simply on the material, which decay after exposing to a high temperature. [15]

5.3 Inkjet printing

Nowadays, the inkjet printers are not used only in offices and homes for texts and documents printing. Development of this technology might seem inactive. However, the opposite is truth and two-dimensional (2D) printing development rise and improve. Ten years old inkjet printer in comparison with an inkjet printer, which was made today, is exponentially better in every field. Resolution in dots per inch (dpi) is crucial for final antenna reliability and efficiency. The inkjet printers, which were commercially sold since 2005, had maximum printing resolution approximately 4800 dpi to 1200 dpi, in 2015 the printing resolution of commercially sold printers was 9600 dpi to 9600 dpi. The differences between resolutions can be seen in the Figure 6. There are also experiments with three-dimensional (3D) printing of the antenna systems. However, only 2D inkjet printing principle will be described in this chapter. The two-dimensional inkjet printing is one of the methods applied in conductive material coating technology for wearable antenna printing on various surfaces.

FIGURE 6. PRINTING RESOLUTION. 1

The inkjet printers have a wide range of possibilities, designs, and manufacturing applications. Although 2D printer works only in x-y planar, the antennas printed by this technique usually have a great efficiency, which could be, of course, influenced by several external factors. The crucial factor is the density of printed dots called "resolution." Resolution is a measure of individual dots, which are printed in 1-inch wide area. And the second crucial factor is droplet size of ink called dot size. The dot size of electrically conductive ink could be between tens to hundreds of micrometers. The dot size of conductive ink has to be chosen properly according to used inkjet printer, or according to the diameter of its nozzle respectively. Inkjet printing system consists of three main parts. The first part is a conductive fluid cartridge, where electrically conductive ink is stored without air and light access. Access to light and air is prevented due to the fact that air causes oxidation of conductive ink and light causes ink curing. Particles of copper, silver, gold, aluminum and their combination are used as conductive ink, as in the screen printing process. The conductive ink film applied to a given surface is very thin, and therefore, this technique is not suitable for porous surface coating. [23]

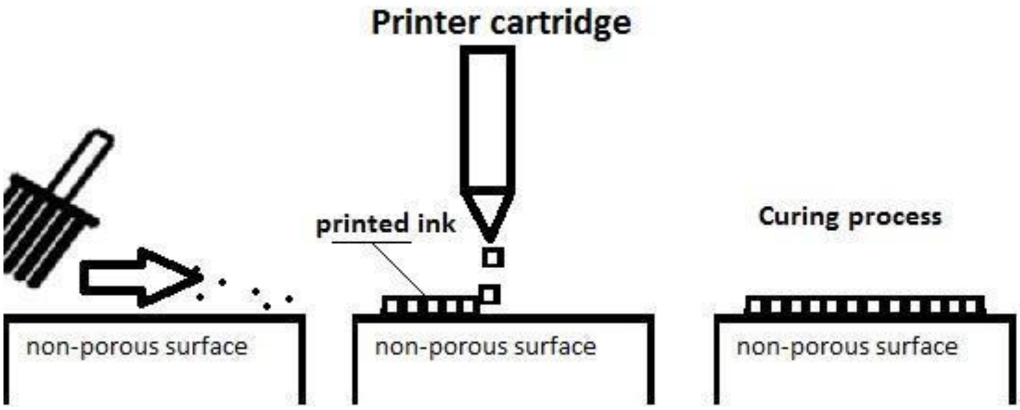

FIGURE 6.1 INKJET PRINTING 1

The second part is Piezo print head, and the third is printing area. Piezo print head is a main and crucial component of the printing system, which mostly determines the final form of printed pattern. Piezo print head is precisely placed in guide grooves. Movement of Piezo print head is procured by two accurate servomotors in two dimensions (x-y) and controlled by printing control system. Piezo print head is based on the principle of the voltage supplied crystalline silicon. The voltage deforms the crystal into various shapes. These shapes depend on the voltage – this phenomenon is called the piezoelectric effect. The silicon crystal is controlled by voltage placed in Piezo print head. The amount and flow rate of electrically conductive ink is controlled by the quantity of electric charge or voltage. There is also so-called heating coil, which cures the conductive ink, and temperature sensor with control feedback. There is a nozzle with a diameter about 100 micrometers on the very end of the Piezo print head. Conductive ink passes through this nozzle directly to printing area. If the nozzle gets blocked by an unknown particle, or simply by cured ink, there are only two way how to fix this issue. The first option is an exchange of whole Piezo print head, and the second option is ultrasound cleaning. The Piezo print head is placed inside the special modified bowl, which is inserted into ultrasound cleaner. This process is similar to jewelry ultrasound cleaning. The last part is the printing area.

Printing area has to be clean without any foreign particles. As was mentioned the porous surfaces are not suitable for this conductive material coating process. Correct viscosity and surface tension of conductive ink are crucial. Viscosity determines how deep the ink goes into the porous material. For instance, the conductive ink of a higher viscosity is used for printing on textiles, which have more porous surface than cork; and for printing on cork surface, the conductive ink of a lower viscosity is used because of smaller dimensions of pores in the surface.

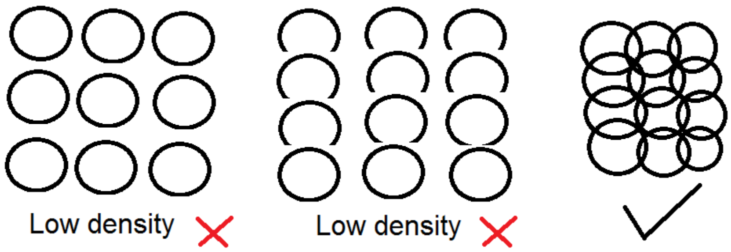

FIGURE 7. PRINTING DENSITY

The ideal humidity together with a temperature of immediate surroundings belongs among a several fundamental requirements for the successful printing process. Strict requirements on humidity and temperature are not necessary if the printing process has only graphical function. Dysfunction of the whole electric circuit can be caused by short-circuit of even the slightest fracture. Sufficient print density is another essential print requirement. Connection interruption, and thus dysfunction can be caused by low print density, as can be seen, it the Figure 7. On the other hand, too dense printing density can cause insufficiently cured conductive ink, and consequently conduction path cracking or smearing. Printing density is set on each inkjet printer modified for conductive path printing individually.

5.4 Traditional fabrication

Traditional fabrication has almost same production steps as a flexible PCB (printed circuit board) fabrication. PCB is dielectric board with a thin electrically conductive layer on the surface. The surface of PCB is metalized by copper or copper alloys. Copper is used due its electrical properties. Dielectric part of PCB is usually made of rigid and non-flexible dielectric, however during last decade flexible PCB has taken remarkable place in the electronic market. Flexible PCBs are used and applied in places where is not possible to use the classical rigid PCB made of Cuprextit, mainly in places, where is the PCB exposed to flexural stress. The flexible PCB with the deposited photosensitive layer is commonly produced and sold. Photosensitive layer cannot be exposed to daylight or UV light during transportation, manipulation or storage. Therefore PCBs are distributed covered with light impermeable foil. PCB with photosensitive layer can be easily devaluated only in few minutes of daylight expose. Flexible PCB is developed by following steps:

1. Step: Antenna pattern has to be printed onto PET transparent foil; this foil is used as an antenna mask. Printer resolution is crucial in this step; therefore, minimum printing resolution is 600 dpi. The pattern should contain describing text to proper orientation of the mask.
2. Step: Cover foil is replaced from the conductive side of flexible PCB. After that, the PCB is placed with the dielectric side to a supporting platform made of foam rubber providing a tight connection between the mask and the PCB. Printed mask is pressed on PCB conductive side by transparent Perspex. And this sandwich set is joined with clamps.
3. Step: Sandwich set with Perspex, PCB and mask are inserted into UV light source for approximately six minutes. Step 2. and Step 3. Has to be done very quickly due to daylight, which is affecting the photosensitive structure of PCB. The using of a light source which radiates UV light is not recommended in this step. After six minutes uncovered part of the photosensitive layer is ready for etching. Mask covered part is now cured and photoresistive.
4. Step: In this step, the sandwich set is dismantled, and tray with 0.7 -1.5 % NaOH (sodium hydroxide) solution is prepared by water and concentrated NaOH mixing. This solution etches only that part of photosensitive layer which was not covered by the mask. This process takes about one minute. PCB has to be washed after this step in clean water.
5. Step: The etching process can be done by several chemical etching solutions. Usually, Sodium Thiosulphate (Na2S2O2) is used. Sodium Thiosulphate solution is poured into a tray and heated on 30 - 40°C.The temperature cannot be higher than 50°C due to solution decay. Etching process has to be controlled every 5 minutes. Properly etched PCB is easily recognizable by visible antenna

pattern. Sodium Thiosulphate is then washed away with clean water. The surface can also be washed and cleaned in an acetone bath.

6. Step: The photoresistive layer covering conductive part remains on the surface. The remained photoresistive layer is removed with highly concentrated sodium hydroxide solution. The solution can be reused, even if the solution changes its color during repeated operations.

5.5 Self-adhesive electrically conductive foil technology

The key aspect of this technology is cheap and effective fabricating process of wearable antennas. This technology is widely used in amateur antenna design experiments, mainly to its low-cost price. Self-adhesive conductive foils made by different producers tend to have different electrical properties, which can be fundamentally different. Thus, the conductive foil is chosen with respect to required parameters. Conductive foils are mainly made of copper. The main advantage of copper foil is the fact that can be extremely bent without any changes in the crystalline lattice; this feature is perfect for wearable applications. Furthermore, cutting of foil into the shape of antenna pattern can be done in the amateur workshop. Cutting can be done by scissors or blades; however the pattern accuracy may not be as perfect as needed. Nevertheless, there is the possibility of copper foil etching by the same process like for PCBs. Etching process of copper foil proceeds as follows:

1. Step: The positive mask is cut by the PC controlled cutting plotter. Cutting plotter uses a knife to cut the foil into antenna pattern. Mask is cut from self-adhesive waterproof foil. There several types of plotters such as drag-knife, flat-bed, or drum type. The edges of the foil have to be sharply cut without any damages, which can sometimes be caused by a blunt knife. Moreover, conductive foil has to be straightened, cleaned and prepared for mask bonding.
2. Step: Mask is thoroughly bonded to the conductive side of the foil. There cannot be any air bubbles under mask foil due to possible inaccuracies in the final product. Mask has to be removed if there are some air bubbles under mask foil. Mask foil cannot be pierced; otherwise, the etching solution can get through. This means that the foil cannot have any permeable damages. If there are any damages the foil has to be changed and the whole process has to be repeated.
3. Step: Base paper is placed on the adhesive side to prevent any adhesive damage during etching. The base paper has to be fitted flat without any flexion.

4. Step: Concentrated ferric chloride (FeCLl3) soil, which is heated to approximately 40°C, is used for copper foil etching. Copper foil is inserted into prepared tray face side down and has to be checked every three minutes. The etching rate depends on chloride concentration
5. Step: The pattern has to be visible after 20 -30 minutes. The foil is removed from a tray. If the pattern is completely developed, it can be washed in clean water. Base paper is not removed until the foil is dried and prepared for application to a textile base. [18],[19]

6 Conductive fibers implementation

Another way to produce a wearable antenna is to integrate conductive fiber into the textile. These methods are mainly suitable for mass production because of high acquisition and operating costs. However, these issues will gradually disappear with the expansion to other sectors of electronics and electrical engineering.

This technique involves sewing or weaving the conductive fiber so-called “filament” into the textile. The conductive textile is composed of two parts, a non-conductive textile base and a second layer containing conductive fiber comprising the active part of the antenna. Monolithic or woven fiber from multiple threads is integrated into the textile. Different fibers have different electrical characteristics, the purpose of use and mechanical resistance – these parameters are determinative.

The complex connection is usually done by soldering. The conductive fiber is integrated into the textile by modified computer-controlled sewing or weaving machines. The properties of these antennas are determined by the accuracy of the machines, which is determined by their resolution as well as the fiber thickness of the base textile. All these operations and the properties of textile antennas made by these technologies and used materials will be described in the following chapter.

6.1 Electrically conductive metallic filament

Electrically conductive metallic filament is known as the “conductive fiber”. It can be made of several conductive materials. Conductive fiber is defined by the electrical resistivity in the case of single fibers. The electrical resistivity ρ (rho) is determined by:

$$\rho = R\frac{A}{l} \quad [\Omega\cdot\mathrm{m}],$$

where R is the electrical resistance measured in ohms [Ω], A is the cross-section of conductive fiber measured in square meters [m^2] and l is the length of conductive fiber measured in meters [m].

Conductive fiber is consisted of one conductive fiber (Figure ...A), several conductive fibers (Figure ...B),, one non-conductive fiber and several conductive fibers (Figure ...C), or composed of one conductive fiber and several non-conductive fibers (Figure ...D),. It shows that there are also several combinations and possibilities of mentioned fiber types. These fibers are suitable for application in wearable components mainly as a part of wiring or for antennas themselves.

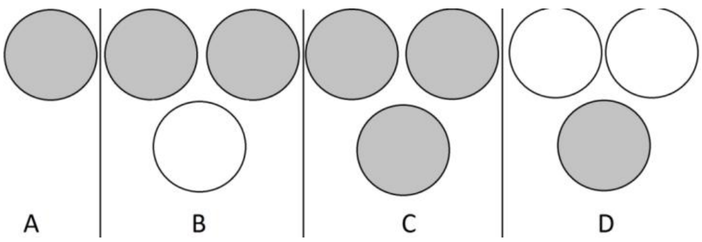

FIGURE 8. CONDUCTIVE FIBERS.

6.1.1 Types of conductive fibers

The three mostly used conductive fiber fabrication processes will be mentioned in this chapter. The first one is conductive fiber filled with electrically conductive carbon fiber composites. These composites can be cavity-shaped filled with halogens, which influence their electrical properties. The distance among the single carbon fibers components, as well as the distance among the single metallic-filled fibers components, determines final yarn conductivity. The non-conductive fiber serves as a carrier of electrically conductive part of the fiber. Electrically conductive part is unevenly placed through the whole diameter of conductive fiber.[20],[21]

The metallization of the non-conductive filament is the second fabrication process. The principle of metallization fabrication is based on depositing of conductive material on the non-conductive filament. It works on the same principle as metallization of PCB. The filament is inserted into metallization electrolytic bath, where metallic layer is deposited on the surface of non-conductive fiber in the presence of direct electric current. Scheme of metalized conductive fiber with nonconductive yarn core is in the Figure 9. The thickness of deposited material can be various. The metallic layer is made of highly conductive copper, which can be additionally covered with a thin silver layer to prevent oxidation and improve conductivity. The last mostly used fabrication method is the usage of fibers, which are fully made of conductive materials. These fibers have usually metalized surface with any of the precious metals. Precious metals such as gold, but mainly silver, are used for the improvement of mechanical and electrical properties as was mentioned. [24]

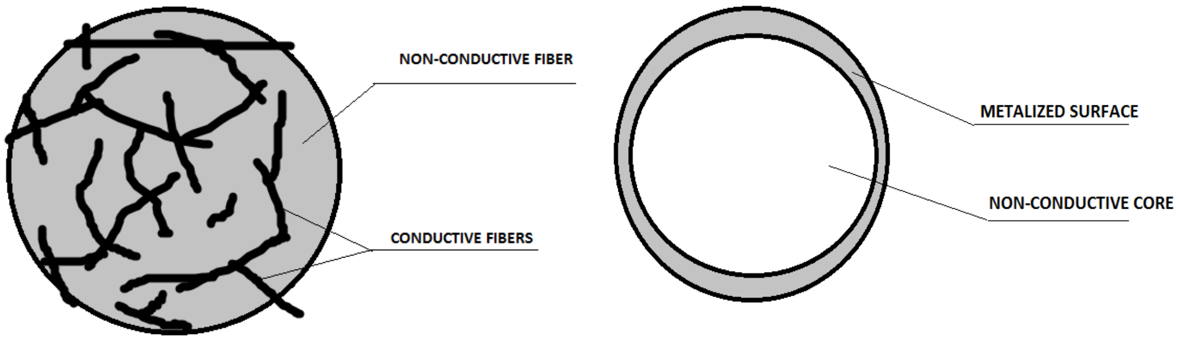

FIGURE 9. CONDUCTIVE FIBERS 1

There are plenty of electrically conductive prefabricated textiles. They are fabricated as electrically conductive sandwiches with their dielectric base or as a single conductive textile material. Crucial factor of these materials is the electrical conductivity Sigma- σ, it is defined as:

$$\sigma = \frac{1}{\varrho} \ [\mathrm{S/m}] \qquad (0)$$

Electrical conductivity is the inverse of electrical resistivity.

6.2 Weaving technology

The weaving technology is the next possibility of electrically conductive textile fabrication. This technology is more than five thousand years old. The production of electrically conductive fabric has been rapidly growing since 1985. This is mainly due to the development progress in the field of wearable electronics. [25]

Weaving is fabric production technology, where two sets of yarns are woven together into one complex fabric. There are two types of threads. The first thread, which is running lengthwise, is called “the wrap” and the second, which is running laterally, is called “the weft.” The fabrics are different from each other in cross-ratio. The easiest and most common cross-ratio is 1:1. The lengthwise running threads are parallelly stretched in two frames. The threads are divided into two groups: the first group is composed of every even thread, and the second one is composed of evere odd thread. The even threads are lifted up in the first phase of the process. Then, there is a gap for passing of laterally running threads – “weft” from the one side to the other – this process is called “threading.” In the next step the odd threads - are lifted up, and weft passes back through the gap. These two steps are repeatedly done until the required pattern passing through the entire width of fabric is not completed. The number of threads is changed with respect to cross -ratio.[26]

The weaving technology is suitable mainly for fabrication of the larger antenna patters. This technology is not suitable for fabrication of small antennas and complicated antennas patterns.

Weaved textile, so-called e-textile, is self-supporting textile structure, It means that there is no base textile and conductive threads are the part of the main structure. There are two main types of e-textiles: e-textile composed of a group of conductive threads, or e-textile composed of electrically conductive and non-conductive threads. The electrical properties of an antenna system can be negatively influenced by a different position of conductive threads in the textile structure. Different positions of conductive threads are shown in the figure 10. The conductive antenna pattern is created by the specific value of the thread cross-ratio. The electric properties are directly influenced by conductive threads cross-ratio; this value shows the number of conductive thread cross in the one row. The side, where is the number of the conductive threads more evident is called “conductive side”, and the side, where is the number of conductive threads less evident is called “non-conductive side”.

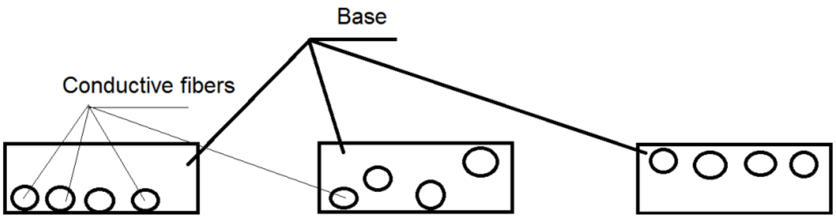

FIGURE 10. POSITION OF THE THREADS. 1

The experimental researches of antennas applications widely use e-textiles as a perspective material in the electrical engineering development. The antennas and sensors made from e-textiles are already used: for the health monitoring systems, in the sporting monitoring devices, in the workers monitoring and logging systems, for the soldiers real-time position monitoring systems, and for drivers monitoring.

The increased losses in the dielectric part of the antenna could be caused by the electrically conductive pattern deformation. Necessary adjustment of the e-textile edges is another disadvantage. Mainly when the shape of the fabric is cut with scissors, the unraveling of the e-textile edges occur. Otherwise, this type of textile used for the antenna fabrication is suitable, mainly due to its prize, flexibility, and a large range of the product, which are necessary for antenna fabrication, available on the market.

6.3Embroidering of the antenna pattern

The embroidering of the conductive antenna pattern is done manually, or automatically. Automated fabrication is performed by embroidery machines, which can use several conductive threads simultaneously. The manual fabrication is practiced only in experimental or small series, mainly because this type of production is time consuming.

The electrically conductive thread is implemented into the base textile by the embroidery machines. The embroidery machines follow the specific instruction, which are recorded in the memory of the control unit. The electrical properties of the embroidered antenna pattern are at the better level than the electrical properties of weaved antenna pattern. The thread density and embroidering resolution, so-called “single stitch density” or “mesh density”, have to be considered with respect to thread density of the base textile. The thread density of the base textile cannot be a lower than the single stitch density of the embroidery machine. [24]

The manufacturing cost can be reduced by the length of the conductive thread. The length of the used thread is directly proportional to single stitch density, however, the electrical properties are influenced by the single stitch density. The transmission parameter S_{21} belongs among one of these electrical properties, which are influenced by single stitch density of the pattern.[25]

The research, in which the S_{21} parameters were explored, was made by IVŠIĆ and BONEFAČIĆ in 2014. They observed the electrical properties, but mainly transmission parameters S_{21}, and they confirmed context between single stitch density of the embroidered antennas and transmission parameters. These measurements were done by insertion of the ten centimeters long strip with embroidered rectangular mesh between two ports. Transmission parameters of electrically conductive yarn embroidered to base textile with mesh density 1 mm x 1mm can be observed in the Chart 1. The electrically conductive yarn embroidered to base textile with mesh density 1 mm x 1mm has transmission. The full plate has S_{21} equals to -0.3 dB and textile with mesh density 4 mm x 4mm exhibit losses more than - 1.2 dB. The Chart 1 below shows that the antenna pattern embroidered into textile with mesh density around 3 mm x 3 mm with exhibit losses 1 dB is suitable for antenna application in 2.4 – 2.5 GHz band.[26]

Mesh density [mm x mm]	S_{21}, f=2 GHz	S_{21}, f=2.2 GHz	S_{21}, f=2.4 GHz	S_{21}, f=2.8 GHz	S_{21}, f=3 GHz
Full plate	- 0.30	- 0.30	- 0.30	- 0.30	- 0.30
1 x 1	- 0.65	-0.68	-0,70	0.72	-.075
2 x 2	-0.95	-1.00	-1.04	-1.07	-1.10
3 x 3	-1.05	-1.05	-1.06	-1.06	-1.10
4 x 4	-1.30	-1.30	-1.30	-1,37	-1.40
5 x 5	-1.50	-1.45	-1.40	-1.50	-1.60

Chart 1. The transmmission parameters S21and mesh densities (σ=107 S/m) [24]

6.4 Knitting Technology

Knitting technology is old method by which the yarn is transformed into plane pattern. It is simply done by pair of needles or commercially by knitting machines. Knitting is based on multiple loops of yarn, which are in the line. This line of loops is connected with another line of loops to make a row. Different textures could be done due to the different sizes of needles and types of knots. The texture, conductivity and resistivity of knitted fabric are influenced by thickness of the conductive yarn. The fabric produced by knitting technology is very flexible and durable. [27] Weft knitting (a) and the warp knitting can be seen in the Figure 11.

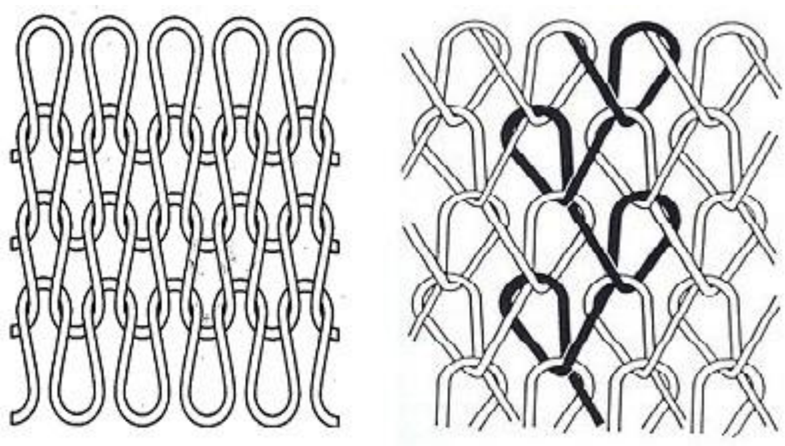

FIGURE 11.WEFT KNITTING AND WARP KNITTIN 1

The main advantage of knitted textile is durability and flexibility. On the other hand, if the structure of knitted textile is damaged there is almost no possibility how to properly fix it. Absence of any glues or laminations like in other textiles overtook its disadvantages and low reliability. However, conductive connection of single wires is provided by direct contact of them. It usually causes unequal conductivity, which could negatively affect the electrical properties of antenna pattern. [29]

7. Printed glass antenna

To provide perfect radio signal reception, new technologies in the automotive industry are continuously being developed. New and improved antenna systems are being constantly introduced. Production of the more aesthetically pleasing antennas increased in last ten years. Furthermore, printing a conductive pattern onto glass is one of these innovations. This conductive pattern is used as an antenna to receive radio broadcasting but other signals, for example a DVB-T (Digital Video Broadcasting – Terrestrial) signal, can also be received. Compared with other conventional antennas, advantages include high durability, easy maintenance and better esthetics. Electromagnetic signals can be received by optimizing the shape and size of printed conductors. [30]

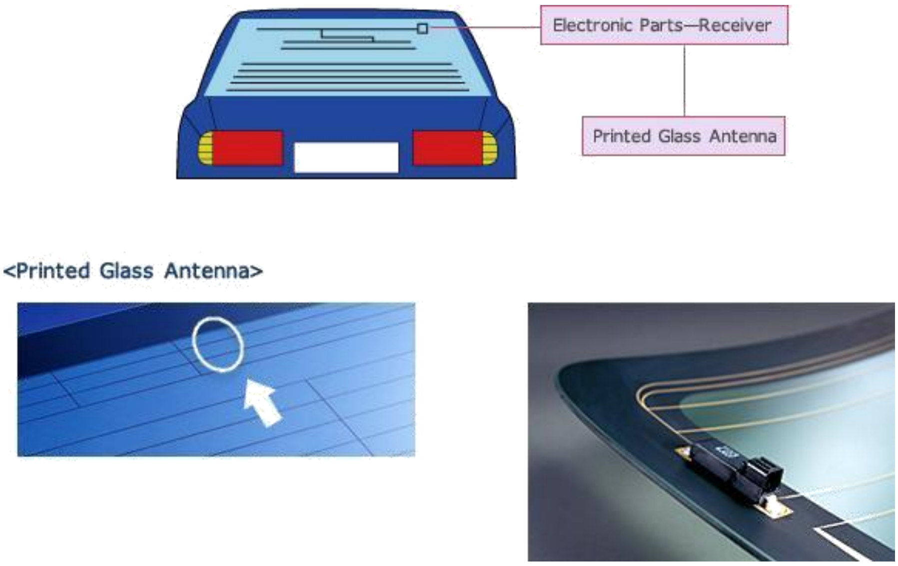

FIGURE 12. PRINTED GLASS ANTENNA. 1

8 .Non conductive materials properties

Non-conducting materials will be described in this chapter. They are mainly used as a carrying layer, so-called "base", for conductive coating or for implementation of conductive parts. Non-conducting materials used in antenna fabrication process have to fulfill required electrical and mechanical conditions as well as electrically conductive materials. Moreover, these materials cannot be restrictive for the user or for the device, which is equipped with this type of antenna.

The base of antenna has to be durable and flexible, while the mechanical and electrical properties remained constant. Unfortunately, such a material does not exist in the real world yet. For instance, the temperature changes, the surrounding humidity, mechanical deformations and other conditions have to be included in computation and simulation of the antenna design. The function of the antenna can be affected by all of these conditions. The diametrical changes can occur in the final results, if the thickness of the base or the base humidity is changed. Therefore, the possibility of the surface treatment or impregnation has to be taken into consideration. Finally, the reliability and effectiveness of the antenna is directly proportional to the properties of the used non-conductive material.

The polyester (PES) thread or yarn belongs among the most used materials. The yarn made of thread was invented in early 1830s [31]. The PES yarn is not water-absorptive, but the non-impregnated base made from PES yarns retains the humidity. The natural cotton or hemp yarns are usually implemented to PES yarns to improve the lifetime, flexibility and durability. In fact, pure PES yarn is subject to oxidation processes and loses its mechanical conditions in the course of time. Its endings and surface begin to crumble and fray. The polyester thread can be shaped into several profiles. There are hollow profiles which improve the thermo-insulating characteristics and overall flexibility. The non-conductive PES yarns can be exposed to the temperature up to 260° C. Under this temperature the crystalline lattice remain the same, thus the material does not change its shape. [31]

The relative permittivity is the material constant, which is given by equation:

$$\varepsilon_r \frac{\varepsilon}{\varepsilon_0};$$

The absolute permittivity is expressed as a ratio, which is comparative to the permittivity of vacuum. This constant is a linear ratio coefficient between electric displacement and the electric field strength and is crucial for computation of the electrical properties of an antenna.

9. Numerical and Practical model of the patch antenna

The patch antenna design was chosen for the wearable antenna fabrication. The 3D textile (figure 13) was chosen as the base for self-adhesive copper foil. The patch antenna is composed of simple geometric shapes, therefore is suitable for experimental fabrication. The main advantage is wide radiation pattern of this antenna, which radiates perpendicularly from the antenna at the angle of 90 degrees. It is especially advantageous due to fact, that the radiation angle is not affected by a human body. ¨

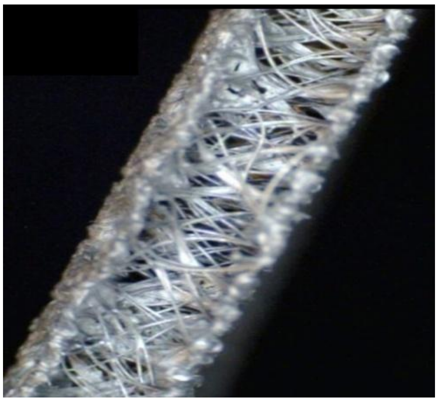

FIGURE 13. 3D TEXTILE 1

9.1 Fabrication

Fabrication is done in the following steps. In the first step; the 3D textile and conductive copper foil are cut into defined shapes. Secondary, the conductive copper foil is bonded on the 3D textile as a ground side. The antenna pattern is printed and cut from copper foil into antenna shape. Afterwards, the copper foil is bonded on the opposite side of the 3D textile. Finally the SMA connector is soldered. Not only is this sandwich set cheap, but also suitable for the wearable antenna application. The flexibility, lifetime and durability belong among its properties.

9.2 Numerical model

The bandwidth of the antenna is approximately 2.4 GHz. This value will be lately adjusted and more specified. The 2.4 GHz bandwidth is used for Wi-Fi communication. The Wi-Fi is generally used denomination for IEEE 802.11wireless standards of wireless communication in information technology and mobile communication. The development of Wi-Fi communication caused strong interferences in 2.4 GHz bandwidth. This problem was solved by the licensing of the authorized channels. There are thirteen authorized channels in the Europe and the signal-to-signal gap is 5 MHz.

9.3 Practical part

The resonance frequency has to be calculated precisely, due to the fact that the frequency of 2.4 GHz is not appropriately accurate for the antenna purpose. All thirteen Wi-Fi channels used in the Europe have to be taken into account. The maximum frequency (f_{max}) and the minimum frequency (f_{min}) are substituted in:

$$f_{REZ}=\frac{f_{max}+f_{min}}{2}, \quad (1)$$

where f_{REZ} is the resonance frequency. The required frequency is simply calculated from arithmetic average .The values (f_{max} and f_{min}) can be found in Chart 2. Thus, the resonance frequency is:

$$f_{rez} = 2.442 \text{ GHz}.$$

Channel number	**Middle frequency [MHz]**
1	2412
2	2417
3	2422
4	2427
5	2432
6	2437
7	2442
8	2447
9	2452
10	2457
11	2462
12	2467
13	2472

Chart 2. [31]

The approximate dimensions of the antenna pattern are calculated after the material and antenna type selection with respect to wearable application. Requirements for wearable antenna: available materials, position on clothes, dimensions of the antenna, and fact that the user cannot be limited while using it. The total approximate antenna dimensions were calculated according to the web application, which is available on the internet. [32]

The maximum edge length of the antenna should not exceed 60 mm. The overall dimensions correspond and accept the requirements of wearable antenna design.

The real width of the patch antenna is given by the equation:

$$w = \frac{c_0}{2\, f_{REZ}} \sqrt{\frac{2}{\varepsilon_r + 1}}\,, \tag{2}$$

where c_0 is the speed of light in vacuum, f_{REZ} is the resonance frequency of the patch antenna, and ε_r is the relative permittivity of the base substrate (3D textile). The changes of the wave propagation at the boundary of the substrate and the antenna pattern made of copper foil are calculated. However, the effective permittivity ε_{eff} is necessary to calculate at first. The effective permittivity ε_{eff} can be described by equation:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{w}\right)^{-\frac{1}{2}}, \tag{3}$$

Where ε_r is the relative permittivity of the substrate, h is the height of the substrate, and w is the width of the patch antenna. Finally, the antenna shortening Δl has to be calculated for the antenna length determination. Given that:

$$\Delta l = h * 0.412\frac{(\varepsilon_{eff} + 1)\left(\frac{w}{h} + 0{,}264\right)}{(\varepsilon_{eff} - 1)\left(\frac{w}{h} + 0.8\right)}, \tag{4}$$

where h is the height of the 3D textile substrate, ε_{eff} is the effective permittivity, and w is the width of the antenna pattern. The final length of the antenna pattern is computed using following equation:

$$l = \frac{c_0}{2 f_{REZ}\sqrt{\varepsilon_{eff}}} - 2 * \Delta l\,, \tag{5}$$

where c_0 is the speed of the light in vacuum, f_{REZ} is the resonance frequency of the antenna, Δl is the antenna pattern shortening and ε_{eff} is effective permittivity. The conductance of the antenna has to be computed due to impedance matching by equation:

$$G = \frac{w}{120\lambda_0} * \left[1 - \frac{1}{24}(k_0 * h)^2\right], \tag{6}$$

where w is the width of the antenna pattern, λ_0 is wavelength in free space, k_0 is the wavenumber and h is the height of the substrate. Wavelength is given by:

$$\lambda_0 = \frac{c_0}{f}, \quad (7)$$

where c_0 is the speed of the light and f is working frequency. Wavenumber is computed by the equation:

$$k_0 = \frac{2\pi}{\lambda_0}, \quad (8)$$

where λ_0 is the wavelength. The edge impedance of the microstrip is determined by:

$$R_{EDGE} = \frac{1}{2\,G}, \quad (9)$$

where G is conductance of the antenna. Finally, it is necessary to compute the dimensions of the tuning gaps of the patch antenna. The tuning gaps of length l a width w_{GAP} are computed from the equation:

$$l_{GAP} = \frac{l}{\pi} arc\ cos\left(\frac{R}{R_{EDGE}}\right), \quad (10)$$

where R is required impedance 50 Ω and R_{EDGE} is the edge impedance of the patch antenna. The final dimensions are computed after substitution to the equations. These values are written in the Chart 3.

3D textile + self-adhesive copper foil		
ε_r	1.3	[-]
w	48.8	[mm]
l	54.6	[mm]
h	3.4	[mm]
l_{GAP}	3	[mm]
f_{REZ}	2.442	[GHz]
wf	16.7	[GHz]

Chart 3.

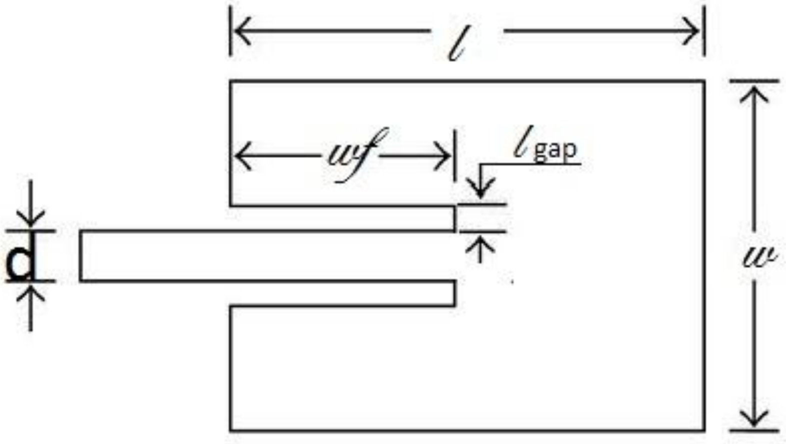

FIGURE 15. ANTENNA DIMENSIONS. 1

9.4 Antenna simulation in CST Studio Suite

Simulation was done in simulation software called CST Studio Suite. This software is simulating tool for electromagnetic devices. It has built in optimization protocol for the dimensions of the antenna due to its resonance frequency.

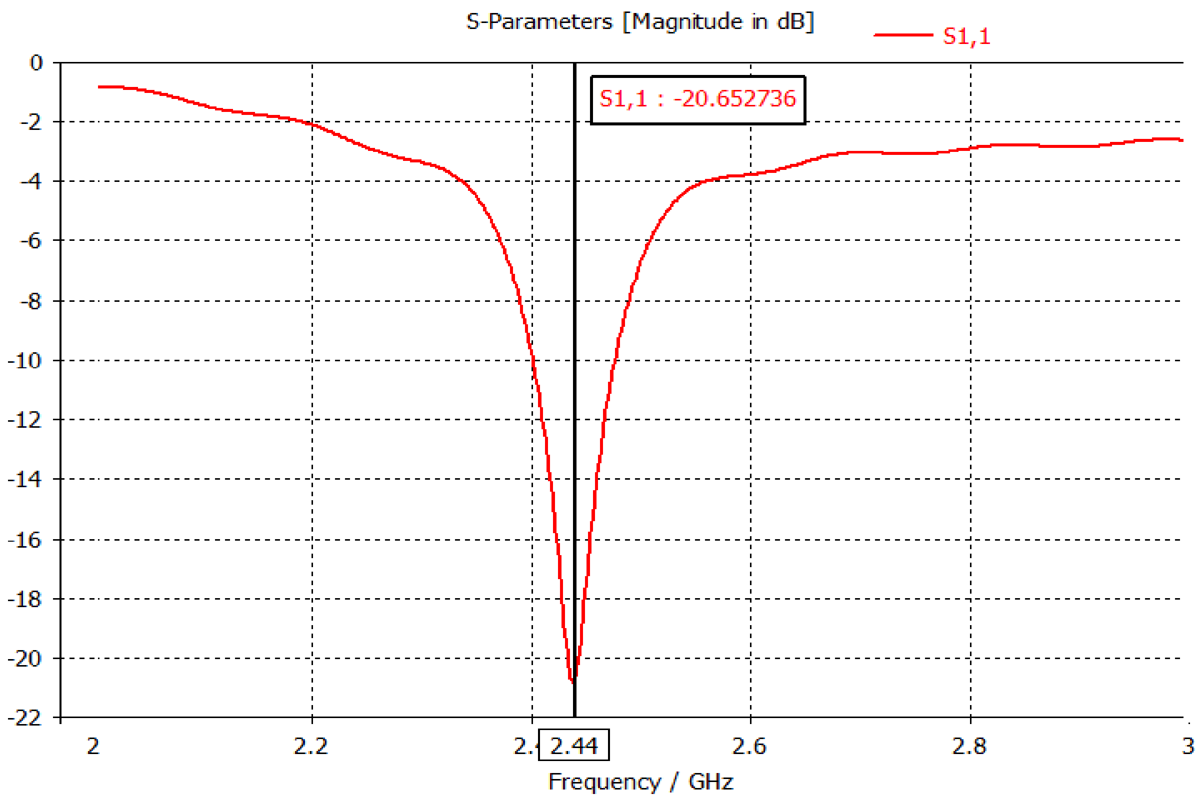

Figure 16. S-parameters[dB] vs Frequency [GHz]

Values of the reflection coefficient are depicted in the Figure 16. The frequency range is 2 – 3 GHz. The resonance frequency is 2.442 GHz according to the Figure 16.. The angular width is 60.7 degrees and the main lobe direction is 12 degrees. It can be caused by the parasitic radiation of the SMA connector and by parasitic losses in the micro-stripe.

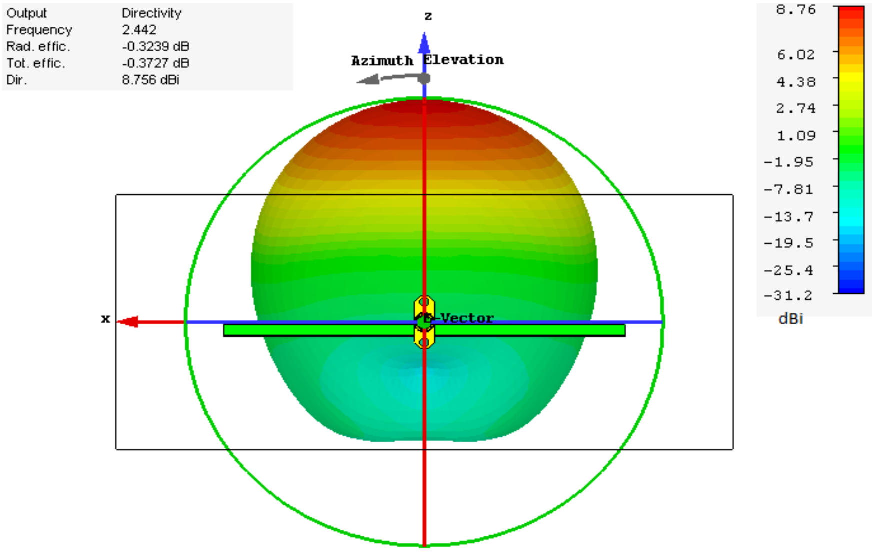

FIGURE 17.DIRECTIVITY 1

The radiation characteristic shows that electromagnetic waves are propagated perpendicularly from the antenna surface. Most of the energy goes up to free space in the opposite direction from the imaginary human body. This direction was chosen intentionally. The antenna should be eventually placed on the arm or on the back. The bandwidth covers the whole range of Wi-Fi channels used in Europe.

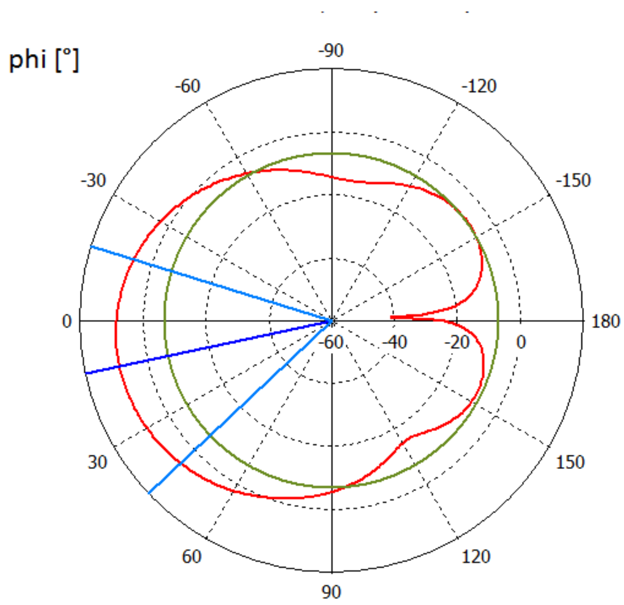

FIGURE 18 THE RADIATION DIRECTIVITY 1

9.5 Real model

The real model was fabricated by self-adhesive conducting copper foil. Copper foil has is distributed with electrically conductive adhesive. The thickness of the copper foil is 0.35 mm. The surface of the copper foil is pure without any surface finish. The copper foil should have a protective coating in case of outdoor using.

The SMA connector is soldered on the surface. The soldering has to be done quickly and the soldering time has to be limited. Otherwise the damage of the 3D textile is unavoidable. The resonance frequency shifted and raised to f= 3.52 GHz; as can be seen in the Figure 18 . The S-parameters were measured on the network analyzer R&S ZLV (9 kHz – 6GHz).

The cutting with scissors is not the most accurate fabrication technique; however the measured results are not far from the simulation results. The bandwidth of the antenna decreased. The directivity and gain protocols and measurements could help to compare these two antennas more precisely.

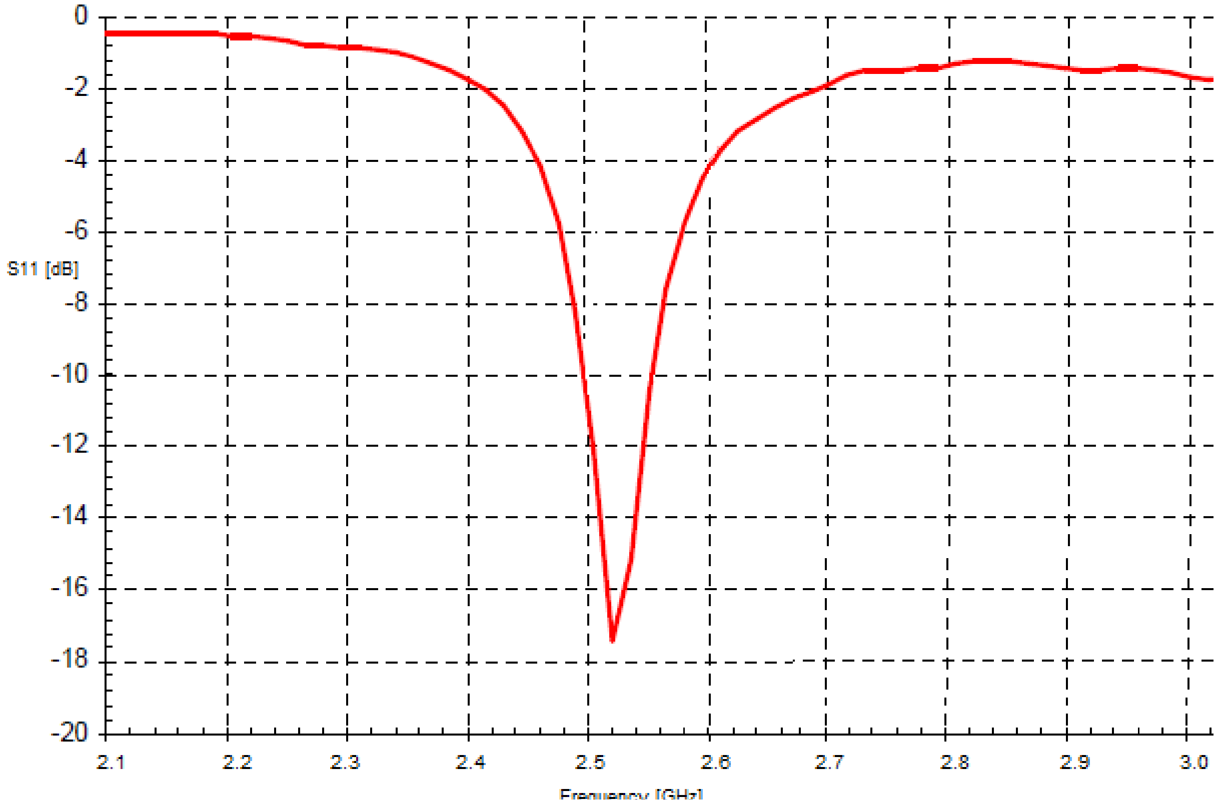

FIGURE 19. S11 [DB] VS FREQUENCY [GHZ] 1

8. Conclusion

Two main goals of this bachelor´s thesis were the description of fabricating process and properties used in antennas that are made from non-conventional materials and the description of materials and technologies used in wearable antennas. Only the most common and verified processes were selected. It means that minor experimental manufacture procedures have not been described. The style in which this publication is written was chosen due to abstention of complete and concise summary and description of used technologies in wearable antennas applications. It may serve as an education tool for those who want to learn something new in this fast growing field of electrical engineering.

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