An Investigation into the Feasibility of the Integration of Microwave Circuitry Into a Woven Textile

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CONTENTS

1. INTRODUCTION.

This PhD document is in support of the practical work carried out by the Author over the 3 years of the M.Phil and PhD research period between October 2003 and October 2006.

Recent times have seen significant advancements in mobile communications. No longer is a mobile phone used solely for making phone calls. The Blackberry, Apple IPhone and other Android[1] phones offer the user the opportunity to remotely keep in touch with, amongst other things, business, news events and also to keep socially connected with friends and family. This is available via email, face to face phone calls and access to the internet, all offered on the latest mobile phone devices.
As with the Apple IPhone, Androids offer the user various apps available to download.
As stated on the Android website,

The Android system and the phones that run it are powerful tools that allow users almost unlimited possibilities[2].

With the development of apps[3], it may not be unimaginable to have an app that interacts with clothing in some capacity. Evidence of this has been seen in CuteCircuits T shirt OS[4].

With these advancements in the mobile communications sector, it is possible to integrate GPS (global positioning systems) to allow reasonably accurate positioning and also informal networking using WLAN (wireless local area network) and also the use of Bluetooth technology.
Greater functionality is now offered in small packages. The availability of applications across the range of phones allows the user access to numerous features which can be downloaded to the handset.
All of this functionality is made possible via the mobile phone's internal antenna.
Along with advancements within the mobile communications sector, the textile industry has also been developing technical fabrics. This can be seen in, for example, breathable fabrics.

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[1]Android phones were developed by Android Inc and Google and offer the user a totally different operating system to that of the conventional mobile phone. As with the Apple IPhone, Androids offer the user various apps available to download.

[2] http://androidphone.org.uk/guides/what-is-an-android-phone/
[3] an abbreviation for application. An app is a piece of software. It can run on the Internet, on your computer, or on your phone or other electronic device.
[4] http://www.cutecircuit.com/

Fabrics that allow moisture i.e. sweat, to be taken away from the skin and also in ‘electro textiles’, fabrics that offer electrical properties.

Is it possible that these technical advancements across these differing industries can be brought together? Can the fusion of a conventional rigid substrate and a flexible substrate be successful?

1.1 RESEARCH AIMS AND OBJECTIVES

Through collaboration with the department of Electrical Engineers at Loughborough University, ‘An Investigation into the Feasibility of the Integration of Microwave Circuitry into a Woven Textile’ will investigate and challenge the possibility of taking a section of the mobile communications infrastructure, the antenna, and produce it using conductive yarn and integrating it into a fabric at the point of production. With this, simple textile transmission lines will also be addressed.

The construction of the antenna and the transmission lines would be of a flexible nature using a conductive yarn. Taking a conventional rigid construction and reproducing it successfully using a soft substrate whilst retaining the natural characteristics of a textile is a challenge of high order.

There are various methods for consideration prior to producing the antenna and transmission lines.

These were, screen printing, weaving, knitting and the use of embroidery. Weaving was the chosen option. Contributing methods to this decision were the fact that the Author wanted the antenna to be totally integrated at the point of fabric production and for it to sit within the make up of the fabric and not sit on the surface. The fabric was also required to retain its natural handle and drape. Also access to machinery was a consideration. The woven textiles dept at Loughborough University offers table looms, dobby floor looms and electronic jacquard looms. This does not necessarily mean that the other methods would not be successful.

Screen printing gives the option of speed when producing an antenna but there is a need for a flexible conductive print paste. This also sits on the fabric and would not offer total integration. Potential problems such as the paste cracking and peeling may occur.

Embroidery would give a slight raised surface and would not be part of the initial fabric construction but may be easier to reproduce. Access to knitting machines wasn’t easy in order to produce samples.

1.1.1 RESEARCH QUESTIONS

3 fundamental questions were to be investigated within the research programme. These were as follows.

Is it possible to produce good quality conductors in a range of fabrics?

Is it possible to construct reliable and useful transmission lines and antennas in fabric using these conductors?

What performance can be expected from such components?

1.1.1.1 Is it possible to produce good quality conductors in a range of fabrics?

Prior to this investigation, the Author had already collaborated on a project with electrical engineers. A range of men's luggage/leisure bags with integrated electronic functions had been designed and working prototypes were produced. The work touched on some of the issues that are investigated here.

One such issue was the production of a good quality conductor. Through previous work, the use of fine wires had been explored and reasonable success was achieved. Along with wires, conductive yarns will be sought and investigated for their electrical properties.

Producing conductors across a range of fabrics has differing implications. Heavy and lightweight fabrics may facilitate a conductor differently. One may support the conductor better than the other. Along with this is the use of natural and man made yarns. Would there be any difference between antennas being integrated into a natural or man made fabric?

If various fabrics are explored, this allows an antenna to be integrated into fabrics for all year round use. For example, if the antenna was suitable for a heavyweight fabric only, then this allows use of a garment only during the colder months. A successful outcome would be an antenna that could be integrated into both a heavy and light weight fabric. This allows for an antenna system to be used throughout the year.

1.1.1.2 Is it possible to construct reliable and useful transmission lines and antennas in fabric using these conductors?

One major consideration is that electrical components are generally made of a solid, non flexible material.

The possibility of producing integrating components into a textile gives rise to associated issues. Stable conductivity can be an issue. With a rigid component conductivity would remain stable, would this be the same when constructed from a textile as the textile naturally flexes?

The design of the antenna and transmission lines would be paramount in reliability. Not only would the components be sampled on a traditional hand weaving loom, they would also need to be produced on industrial looms, and to be repeatedly reproduced successfully on both looms is key to continuity.

Testing of the antenna under flexed conditions would not be undertaken during this programme of research.

1.1.1.3 What performance can be expected from such components?

It is hoped that the antenna will radiate to some degree. The conductors produced in the various fabrics will be assessed for their electrical and high frequency properties.

Along with this they will need to be characterised at the frequencies applicable to mobile communications.

Performance will hinge on the chosen yarn or wire used to construct the antenna as high electrical conductive properties will be important in giving a better performance. One factor to consider when testing the antenna would be the connection between the fabric and test equipment. Would it be reliable as a hard substrate would be connecting to a soft substrate?

When testing, frequencies up to 4GHz would be used. The Department of Electrical Engineering have a range of test equipment for undertaking these evaluations and the techniques required for such tests are also well understood by the staff offering greater technical support.

The samples will finally be tested in the anechoic chamber within the Dept of Electrical Engineering.

1.2 STRUCTURE OF THE THESIS

The report is written in a specific manner, simplified but informative so that it will help the audience understand better this subject domain. This is due to the fact the work is carried out across disciplines and should be able to be understood by both electrical engineers and those from a textile and design background.

This document will outline the research topic from its origins; the literature search will show evidence of similar work being carried out by research laboratories and academic institutes and practical experiments will be explained and results documented.

It will also highlight the global market growth expectations and discuss why the lack of commercially available items with integrated electronic functions threatens this growth. Along with this, other target areas will be identified as possible sustainable areas where this technology can thrive and continue to develop and evolve.

To understand the whole process of antennas and how they work is extremely difficult for anyone that has not had practice, or studied the area in detail. With this in mind, included in the annexe is 'Understanding antennas and how they work'. The terminology used can be complicated but the relative sections describe what certain integral elements actually mean.

This is necessary not only to gain a simple understanding of this complex subject, but also allows the audience to grasp a basic understanding.

1.3 RESEARCH APPROACHES AND METHODOLOGY

The programme of research would follow a predominantly exploratory method through a series of experiments. Through reflection of outcomes of these experiments, questions would be asked and alternative working methods sought. The outcome of each experiment would inform the next stage in the aim of answering the research question.

Coming from a Printed Textiles background the Author had no previous working knowledge of the weaving process itself or the setting up of the loom or terminology used but it was the thought of using a woven textile as a means to this particular end that was of interest as it was taking the antenna, which is generally of a rigid construction, and investigating the feasibility of replicating it in a soft substrate.

A lack of specific knowledge, in some respects, was an advantage to the Author as there were no preconceptions to the limitations of weaving. This was an opportunity to challenge traditional working practices in order for the cloth to facilitate a woven antenna.

The preliminary experiments would involve investigating and weaving various woven structures in order to understand the weaving process and how one structure differs from another. The tests will also give the opportunity to sample various yarns in the weft and examine the handle and drape when these varying yarns are woven together.

The structures that were woven would also inform whether a particular structure would be suitable for the integration of wires. Different weave structures such as twills, can result in a quite loosely woven cloth which in turn could leave the wire exposed and vulnerable to being snagged whereas a closer tighter weave, such as a plain weave, would ensure that the yarns and the wire were closely associated, thus virtually eliminating any threat of snagging.

Initially the samples were woven on a hand operated 8 shaft table loom which facilitated 3 different yarns in the warp: cotton, polyester and Tencel. The Yarns were selected as cotton is a natural yarn, polyester is a man made yarn and Tencel, again man made but with a silkier feel than polyester. The various yarns used would indicate whether a wire or conductive yarn would be more suitably integrated with a natural or man made yarn or whether there was no noticeable advantage.

Future tests also examined the possibility of weaving on an electronic jacquard machine using a conductive yarn. This was important as the potential textile antennas would need to be constructed using modern weaving technology and not rely on time consuming hand operated methods.

The structures were designed on ‘point paper’ which has the same look as graph paper. The same structures were also used on the CAD weave system which would allow for a 3 dimensional view of the structure on the computer monitor which gave a clear indication of which yarn was going either over or under another yarn forming the cloth. This also allows the Author to get a clearer understanding of the weave process and along with this, an understanding of various woven structures.

1.3.1 Methodology

This approach to the research can be largely described as Quantitative Research. It does also fall into the Qualitative Research category.

Quantitative research is summed up by Thorndike's statement,

> 'Anything that exists in a certain quantity and can be measured'[5]

This is true in the sense that the results gathered by the Author during these experiments are not open to discussion or argument, they are a measured outcome and in turn these findings will inform the following steps in the investigation. The results can also be replicated once a successful application has been defined.

> 'The ideals of quantitative research call for procedures that are public, that use precise definitions,[6] that use objectivity-seeking methods for data collection and analysis, that are replicable so that findings can be confirmed or disconfirmed, and that are systematic and cumulative- all resulting in knowledge useful for explaining, predicting and controlling the effects of teaching on student outcomes'.

Once the tests have been carried out on the samples, the data or results are collected and analysed. This is where the research falls into the Qualitative methodology. Without analysis of the results the investigation doesn't move forward.

Although being from a textile design background, the research method is more associated in scientific and technological contexts.

With having ascertained how the research would be carried out, the area of wearable electronics would have to be investigated in order to see where the work sits within everything else which was being investigated by various other research laboratories and institutes.

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[5] statement taken from an article by Julie Fierro on Quantitative research www2.gsu.edu/~mstswh/courses/it7000/papers/quantita.htm

[6] Statement taken from the same article by Fierro

1.4 BENEFITS OF INTEGRATING COMPONENTS

Identification of a potential method of integrating antennas for mobile communications frequencies into fabrics can lead to a large range of beneficiaries. For example the technology could be adapted for medical applications in order to monitor vital health signs. However, it is likely that the mobile communications industry would be the main driver for producing items but once the technology was in place, there is no reason why other areas could not be identified as possible end users. Once such technology is available, a system could be conceived where outdoor clothing and equipment such as rucksacks could have both GPS[7] receivers and a simple beacon transmitter so that a current position can be transmitted.

Integration into the materials and equipment would enhance the safety of search and rescue personnel with minimal weight penalty and may also be integrated into 'high end' outdoor equipment for the general public.

Another potential use of this type of technology would be as an aid to the blind and other people with disabilities. The ability of a blind person to 'interrogate' their clothing to choose colour and style to wear would give them considerable independence.

Information on the deaf and blindness blogspot[8] indicates that in general, remembering what type of buttons or zip a garment has is the only way of identifying it. There is an expensive piece of equipment that can be placed on a garment which in turn announces the colour. A development of this into an integrated component may prove to be more successful.

1.5 IDENTIFYING THE RESEARCH AREA

The literature search highlights the areas that are being investigated and at the same time identifies areas that could be possible application areas. A large amount of work is going into wearable entertainment, MP3 players as we have previously seen. This involves the construction of conductive cloth in order to carry an electric current to the integrated component.

However, one particular area of interest is that of textile antennas. This also requires the use of conductive fabric / yarn in order to integrate microwave circuitry into textiles.

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[7] Global positioning system

[8] http://deafblindness.blogspot.com/2010/06/doing-everyday-things-blind-or-deaf.html

Professor Thad Starner[9] highlighted the integration of microwave circuitry within a textile in a newsletter distributed by Techstyle news[10]. He stated that it is a particular area of interest as this topic is fundamental in the evolvement of motion aware clothing. Along with this, the integration of GPS systems and medical monitoring systems are possible. This also shows that the work carried out as described in this thesis was innovative and also in a very much embryonic stage.

1.5.1 What are electro textiles?

Wearables, wearable electronics, technical textiles, techno textiles, smart textiles, intelligent textiles, I-textiles, E-textiles and electro textiles. These are just a number of the terms that are used to describe this particular area of research in which wearable antennas fall.

For ease of reading and unnecessary use of terminology, the term ‘electro textiles’ will be used throughout this document.

The above terms can be used to describe a textile, either for use in apparel, home furnishings or a piece of textile art that has the ability to transfer data or operate an electronic item such as a MP3 player[11] or a mobile phone.

For this function to happen, a chosen or a complete area of the textile needs to be electrically conductive. The conductivity can be integrated in more than one way.

Methods that have been used include fine metal wires woven into cloth, fine wires spun with a carrier yarn, electro-less plating[12], printing onto the cloth with a conductive paste and weaving with a naturally conductive yarn.

1.5.2 Origins of Electro Textiles.

There is no concrete evidence to establish who developed, or what the first item of electro-textile was and when it was produced. The electrical company Philips who, in 1995, devised a project titled ‘Vision of the Future’ explored the integration of electrical components into textiles. This was the first time that concepts of this fusion between electronics and textiles were presented to the public.

Due to the response from the press and public, Philips invested in researching this area from 1998.

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[9] Assistant Professor at Georgia TECH college of computing, USA

[10] Article in issue #20 December 15, 2002 www.thinkingmaterials.com

[11] A personal music player that stores music in its memory and doesn’t play CDs

[12] A chemical process of coating fabrics with a fine layer of copper without the use of electricity

Between 1998 and August 2000, Philips collaborated with Jeans wear manufacturers Levis and produced the first wearable electronic garments (Fig 1) available to the general consumer. The garments produced were a range of jackets that contained communication and entertainment items.

Fig 1 Image of the ICD+ jacket produced by Philips and Nike

The collaboration had successfully integrated a mobile phone and an MP3 player into a wearable garment. The items were hands free and voice activated. A microphone was positioned in the collar of the jacket and the phone could be operated using this. If the wearer was listening to music on the integrated MP3 player it would automatically cut out if an incoming phone call was received. The integrated items were operated via fine wires that were sewn into the seams of the jacket. This allowed for the integrated items to be unplugged when the jacket needed to be laundered.

Levis marketed the jacket through the brand ICD+ (industrial clothing division). This collection is no longer available and it is believed that the minimum quantities that were available were sold through outlets such as Selfridges for around £500 - £600. The jackets though were problematic in the manufacturing. Due to the wires that were positioned in the seams of the jacket, there was considerable wastage as the needles of the sewing machines often went through the wires during production.

Along with Philips, in the late 1990s Massachusetts Institute of Technology (MIT) was also working on electro textiles.

An all-fabric keyboard (fig 2) was developed by the MIT Media Lab which used 2 layers of a conductive metallic organza, and non-conductive material sewn together. This was in a row and column formation. The rows were separated by an insulating layer of nylon netting. The final piece had the appearance of a quilt that had been pieced together in a square pattern. Holes in the insulating fabric allow the row and column conductors to make contact once a user presses down on the keyboard at the correct point. This allows a current to flow from a row electrode to a column electrode.

To connect wires from a microcontroller to the organza, snap press studs were used.

Fig 2 Image of the all fabric keyboard developed at MIT

The keyboard could be folded, scrunched and even put in the washing machine with no adverse effects.

2 LITERATURE REVIEW

The following sections will look at a broad range of applications where electro textiles are being investigated. Although not involving textile antennas, they do demonstrate where electrical conductors were being used and how they were being used and prove that this area is evolving in a broad spectrum. Moving on from that, Textile antenna developments will be explored.

2.1 TARGET AREA DESIGN DEVELOPMENTS

In the early part of the 2000s, the area of electro-textiles was becoming increasingly more popular. The number of research laboratories also investigating this area was increasing and the commercial sensitivity of this area was apparent.

Technical information on this area was very scarce; all that was available was the minimum of details that outlined what the laboratory was working on. Various research projects were being undertaken to establish where this new technology could be applied. The main target areas that were identified were Military, Medical, Fashion/apparel and Sports and Leisure. Applications for the home have been seen in the prototype form and this technology has also been applied in the automotive industry.

The following sections will highlight some of the items and garments where this technology has been applied, its intended usage at the time of the programme of research, and where possible, the developments of the project.

2.1.1 Fashion/apparel

The area of fashion and apparel has seen a number of prototypes developed with very few actually making it to full production. These range from football shirts to business suits to extreme sportswear. The following sections highlight some examples of these applications.

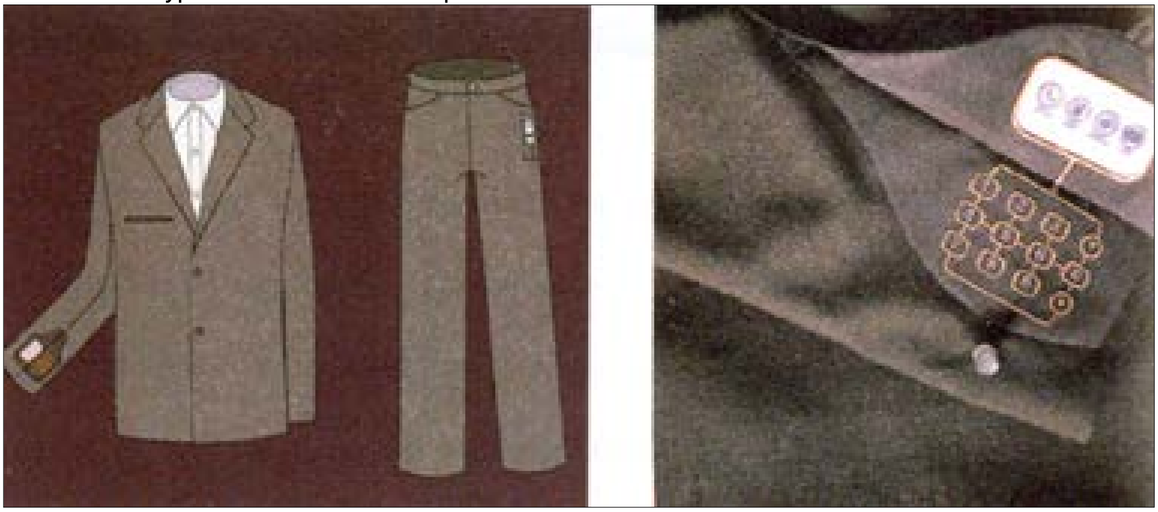
2.1.2 Philips

Following on from the collaboration with Levis, Philips continued their investigations into electro-textiles and this resulted in a collection of prototypes which were exhibited under the title of New Nomads[13].

[13] The collection of prototypes can be seen in the book 'NEW NOMADS' an exploration of wearable electronics by Philips

This collection contained garments that had integrated electronic items. The way in which they were integrated was far more sophisticated than those which were displayed in the ICD+ project with Levis. The collection was aimed mainly at the business user and the sport and leisure sector.

Fig 3 Illustration of the business suit produced by Philips [13] the image on the right shows the embroidered keypad situated under the flap on the cuff



The images illustrate that the suit had the ability to contain everything that the business person would require during the working day. The electrical items such as the mobile phone were miniaturised and would clip on the jacket in the form of an accessory. The keypad was formed by embroidering with conductive thread. It was located under a fold down flap situated on the cuff.

Another business suit was developed but on this occasion it was directed at aircraft stewards/stewardesses. The display screen situated on the cuff can hold all of the relevant passenger information such as special dietary requirements.

Philips again explored the sport and leisure areas in the New Nomads project. A jogging/tracksuit incorporated a personal music player which could be activated using controls that were printed onto the garment using a conductive printing ink. This allowed the user to forward or rewind the player and also stop the music. The volume was controlled using toggles so the wearer could adjust the level of the music whilst running and not having to fumble for the equipment in a pocket.

A snowsuit was also developed for use with skiing or snowboarding (Fig 4). This was developed with the ability to heat up if the wearers' body temperature dropped below a certain level.

Other items that were incorporated into the suit were a GPS system, illuminated warning/hazard sign on the back of the suit to warn others on the ski slopes that they were too close.

Fig 4 illustration of the snowsuit produced by Philips [13] the printed conductors can be seen on the tips of the gloves, used for activating the MP3 player.

A personal music player was also incorporated and this was controlled by printed conductive ink pads on the tips of the gloves. Speakers for the system are situated in the hood and again controlled by a toggle system.

In 2002 Philips collaborated with Nike sportswear and produced sports clothing that could monitor the wearers' performance. These were only available in the larger Nike Town stores.

2.1.3 Military

The Natick soldier centre in Massachusetts[14] has been developing the future warrior system for some time. This integrates electronic systems such as GPS, chemical detectors and wearable concealed antennas into the battle uniform (Fig 5). The detectors and GPS systems could relay real time information to the soldiers' personal computer whilst on the battle field.

[14] http://nsrdec.natick.army.mil/

Fig 5 illustration of the future warrior system [14]

The integrated textile antennas would need to be characterised for near and remote communications. The antenna would replace the 6ft whip aerial that the radio operator normally carries and this would make him much less of a target for the enemy as he wouldn't be identified so easily.

The overall aim of the Natick soldier centre is to convert the uniforms of the future into passive battle dress that can provide electronic/optical power and data transmission to the personal computer along with the incorporation of displays and sensors and integrated antennas.

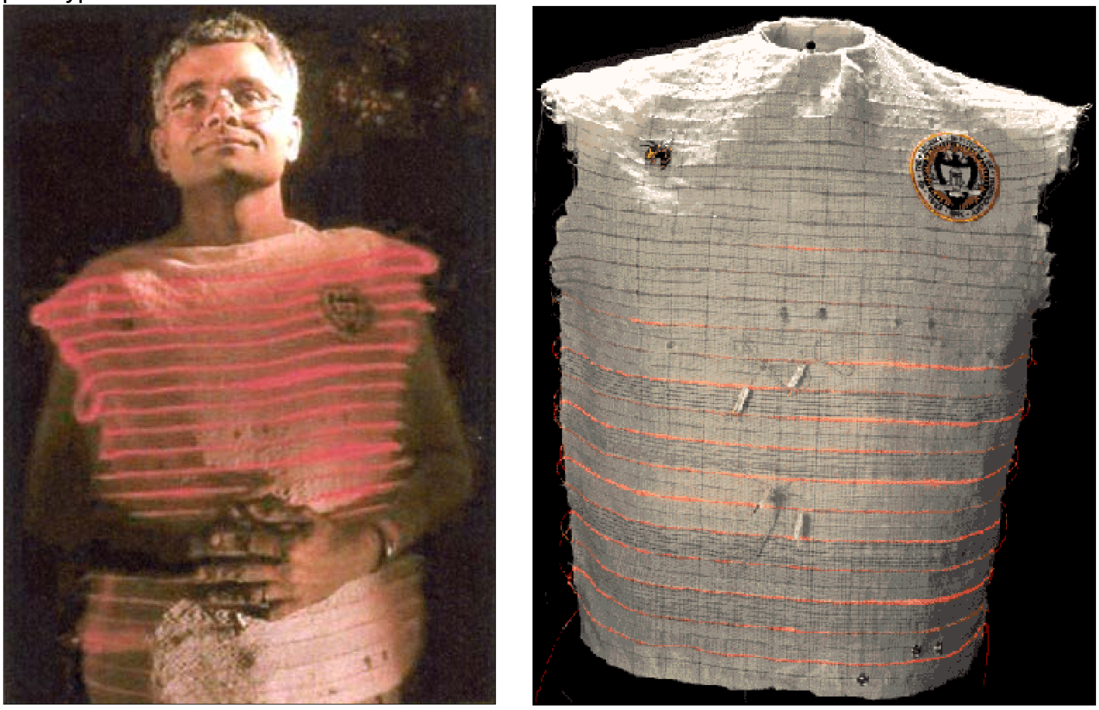
2.1.4 Medical

Although it was not initially developed as a medical application, New York company Sensatex's smart-shirt (Fig 6) was marketed as one.

The shirt is constructed from an electronic fabric and this was formed using a mix of natural fibres, thin wires and optical fibres.

The smart shirt will pick up vital signs from the wearers body. Blood flow, body temperature etc could be relayed to a computer within the vicinity of the wearer. If the readings from the shirt indicated that the wearer was having a heart attack, the electronic sensors could note this and inform the computer which in turn would call a doctor or ambulance.

Fig 6 Photograph of Sundaresan Jayaraman [15] and the smart shirt. Jayaraman is seen wearing the prototype smart shirt.



Sundaresan Jayaraman, pictured in Fig 6, the inventor of the fabric describes it as a wearable motherboard. He suggests it is possible to attach headphones and an MP3 player along with blood pressure monitors by simply having electrical and optical signals zipping through the fabric. Jayaraman added that the possibilities of this are only limited by the amount of memory and the weight of the gadgets hanging from your sleeves[15].

For ease of laundering the sensors were designed to be removed and also helps reduce wear and tear.

2.1.5 Home/Interiors

When the initial literature search was undertaken, there was very little development with electro-textile applications within the home and interiors environment.

Philips had continued to develop electro-textile applications and this included cooking aprons that had the ability to interact with the cooker and also tablecloths that could keep dinner plates warm[16]. Other organisations that were developing prototypes for use around the house

[15] The full article is available to view at http:/msnbc.msn/id/3068740/

[16] Information gathered from a presentation at Nottingham Trent University.

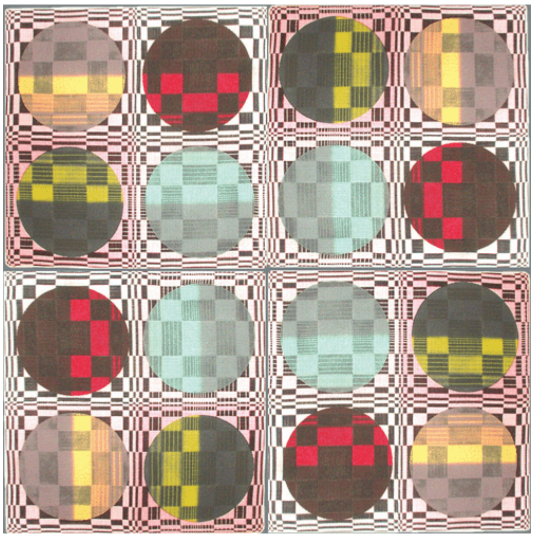
included Brunel University[17] in England and also Massachusetts Institute of Technology media lab[18] in the USA.

Brunel University produced a prototype cushion that used flaps of touch sensitive fabric that worked as a TV remote control. The project was titled Detect. The cushion had interwoven conductive fibres and located and measured the pressure applied to operate the remote control[19]. This could lead the way for remote controls to be incorporated into the arms of easy chairs and sofas at the point of production.

Researchers at Brunel University offered other applications for the fabric. Hospital linens that could prevent bedsores, clothing to assess athletic performance and upholstery in cars that ensures that the vehicles airbags inflate properly by assessing the drivers weight etc.

Researcher Maggie Orth[20] from the media lab at MIT[21] created a colour changing 'electric plaid' fabric, FIG 7.

Fig 7 image of electric plaid [20]



The fabric is woven with conductive fibres integrated and thermo-chromatic inks screen printed to the cloth. Once the fibres in the cloth heat and cool, they change the colour of the cloth.

The fabric's developer Maggie Orth was hoping to gain interest from the Military for clothing that changes colour to blend in with the background which would result in an interactive camouflage.

[17] Design for life centre
[18] http://www.media.mit.edu/
[19] Article available at http:/magma.nationalgeographic.com/ngm/0301/feature3/index.html
[20] http://www.maggieorth.com/
[21] Massachusetts Institute of Technology

MIT have also developed an electronic tablecloth which doubles as a tablecloth game, whether there is a place in the home for such a thing is questionable but it demonstrates the potential breadth of the applications.

Orth has since created many more electro textile pieces which can be seen on her website[22]

Infineon Technologies of Germany designed a 'Motion Detect' carpet which has integrated sensors[23]. The carpet could then be connected to an intruder alarm system to alert business or homeowners of an intruder. The motion sensors could also be used in buildings to detect any movement of the walls. This is important in the detection of possible subsidence which could compromise the stability of a buildings structure.

One project that continued from the work at infineon is the Sensfloor®[24]. This is based on a textile underlay with integrated secors and radio modules Fig 8. The underlay can be integrated under a conventional floor covering.

Fig 8 Image of sensfloor matting [24]

The sensors detect any movement that has occurred on the floor and this information is sent to a control unit where it is analysed to detect what the motion is.

For example, footsteps that begin at a window may indicate that there has been a break in at the premises. This technology can be applied in care homes or institutional care where it can detect if someone has been laying on the floor for a long period of time. This in turn will trigger an emergency call.

[22] http://www.maggieorth.com/

[23] www.innovations-report.com/html/reports/information_technology/report-18175.html

[24] http://www.future-shape.com/en/sensfloor.html

A portable version of the Sensfloor is the Sensfloor mat. The mat holds 32 capacitive sensors per square metre of textile and is only 2mm thick.

Analysis of the data from the sensors indicates whether people are standing or lying on the mat or how quickly people are moving in one particular direction.

The mat is also said to respond to steps and can in turn open doors or detect an unauthorised entry. In care homes or other similar institutions it can register a person leaving a bed or the room. This is important with those who suffer from dementia who may leave the room and not be able to remember where they are from or the way back.

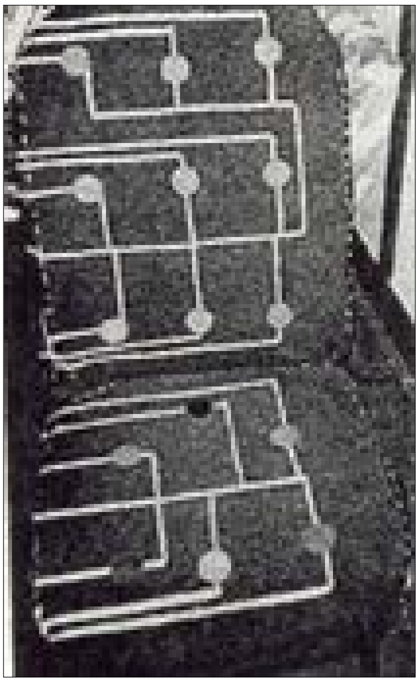
The mat can also be used as a security assist with having the ability to monitor revolving doors and has the option of counting people.

2.1.6 Automotive

There was no significant information regarding smart/electro-textiles in this area with the initial literature search.

An Italian company, Smartex[25], were collaborating with leading automotive companies in a project to produce a smart car seat (Fig 9). The seat would implement a system that could monitor the weight of the person which in turn can control the activation of the cars airbag and also modify the support in the seat to suit the posture of the passenger.

Fig 9 image of a prototype smart car seat with the incorporated sensors [25]



[25] http://www.smartex.it

Along with this they have been involved with other research projects involving the use of smart/electro textiles; many of these include medical application.

More recently German car manufacturer Daimler, have been investigating the use of smart textiles in vehicles.[26] This was to integrate sensors into car seats that monitor various health signs such as the drivers' blood pressure, skin temperature and drowsiness. Under the research project of Insitex, the sensors were integrated into a Mercedes Benz concept car[27].

2.1.7 Canesis

Developments within SOFTswitch technology has allowed for the operation of personal music players integrated into clothing. As the name suggests, this is a soft flexible switching system designed for textiles. It is completely washable and durable. The switching interface system was developed by collaboration between Peratech Ltd and Canesis Ltd. They are the UK subsidiary of Canesis Network Ltd[28]. SOFTswitch technology was integrated into the Burton AMP snowboarding jacket[29] (Fig 10). This allowed the wearer to operate the integrated ipod music player without the need to fumble with pockets and zips whilst partaking in the activity.

Fig 10 photograph of the Burton AMP jacket [29] with the MP3 controls situated on the left cuff

The Burton AMP jacket was only available through the Burton Snowboarding Company.

[26] http://www.plusplasticelectronics.com/Automotive/projects-drive-organic-electronics-in-automotive-industry.aspx
[27] http://www.izm.fraunhofer.de/EN/abteilungen/siit/research/mikrosysteme/insitex.jsp
[28] Formerly known as WRONZ, the Wool Research Organisation of New Zealand
[29] http://www.mobilemag.com/2003/01/08/burton-and-apple-deliver-the-burton-amp-jacket/

Along with Burton, the company O'Neill has developed a Walkie Talkie Jacket (fig 11). The jacket is targeted towards outdoor enthusiasts who venture in unexplored and more remote areas. It enables the user to stay in contact with the group or base station. The walkie-talkie connector is located in the chest pocket for out of the way storage thus keeping your hands free. The speaker and microphone are integrated into the collar. The 'push-to-talk' button on the wind-flab of the jacket enables the user to operate the Walkie talkie.

Fig 11 image of the O'neil 'Walkie Talkie' jacket

2.1.8 Woolongong University

Collaboration between Philips and Nike and the work of Burton with the snowboard jacket have shown that the sports area is a potential target area for electro-textile applications. The technology has been seen in sports undergarments which are used when partaking in sporting activities.

Researchers at Woolongong University, Australia, have been developing the Smart bra (Fig 12).

The bra is constructed with 2 intelligent polymers. One of these polymers generates electricity when it is stretched whilst the other would contract when electricity is passed through it. When the wearer partakes in any form of exercise, the smart bra restricts the movement of the breasts giving the user a more comfortable experience.

Fig 12 photograph of a prototype smart bra showing the sensors which enable the bra to contract and relax

Once exercise is underway the first polymer stretches and generates electricity. A tiny microchip embedded in the bra detects the generated current and sends another electrical signal to the other polymer. This polymer then contracts and tightens the bra straps which in turn provide a good amount of support for the wearer.

2.1.9 University of Bolton

The University of Bolton have also developed a smart bra. This differs considerably from the bra developed at Woolongong University. Professor Elias Siores, the inventor of the Smart bra states that the bra can detect the early stages of breast cancer before it can develop and spread to surrounding areas. The microwave antenna detects abnormal temperature changes in the breast tissue which is generally associated with cancer cells.[30]

No images were available of the smart bra.

[30] http://www.bolton.ac.uk/News/News-Articles/2007/Oct2007-1.aspx

2.1.10 University of Tokyo

Developments by Japanese inventor Susumu Tachi at the University of Tokyo resulted in an 'Optical Camouflage' cloak (Fig 13). When the cloak is worn it gives the impression that it is invisible as images behind the wearer are shown on the front of the cloak.

It is made from a retro-reflective material that is coated with tiny light reflective beads over its entire length. On the back of the cloak tiny cameras are fitted which project the image from the back onto the front giving the impression that the cloak is 'see-through'. At the point of the initial literature search the cloak was not fully functioning. However the device was gaining a lot of serious attention from military experts who could use this technology to move troops into action un-noticed.

Fig 13 Photographs of the 'optical camouflage' cloak from the University of Tokyo

More recently the invisibility cloaking has also been investigated by amongst others Karlsruhe Institute of Technology[31] and also a project by Hyperstealth Biotechnology Corp funded by the US Military called 'Quantum stealth[32]'(fig 14).

[31] http://www.kit.edu/visit/pi_2011_6866.php
[32] http://www.hyperstealth.com/Quantum-Stealth/index.html

Fig 14 image showing a simulation from the Quantum stealth project

2.1.11 France telecom

France Telecom invented a flexible fibre optic screen that can be embedded into clothing[33] (Fig 15). This would allow static or animated graphics to be displayed on a garment. The garment has the capability to download graphics such as logos, texts, scanned images and patterns.

The garment is provided with its own software to enable the user to create individual images online via a dedicated server. A flexible remote control is integrated into a lapel and this then enables the wearer to select new images from the server that can then be displayed on the garment.

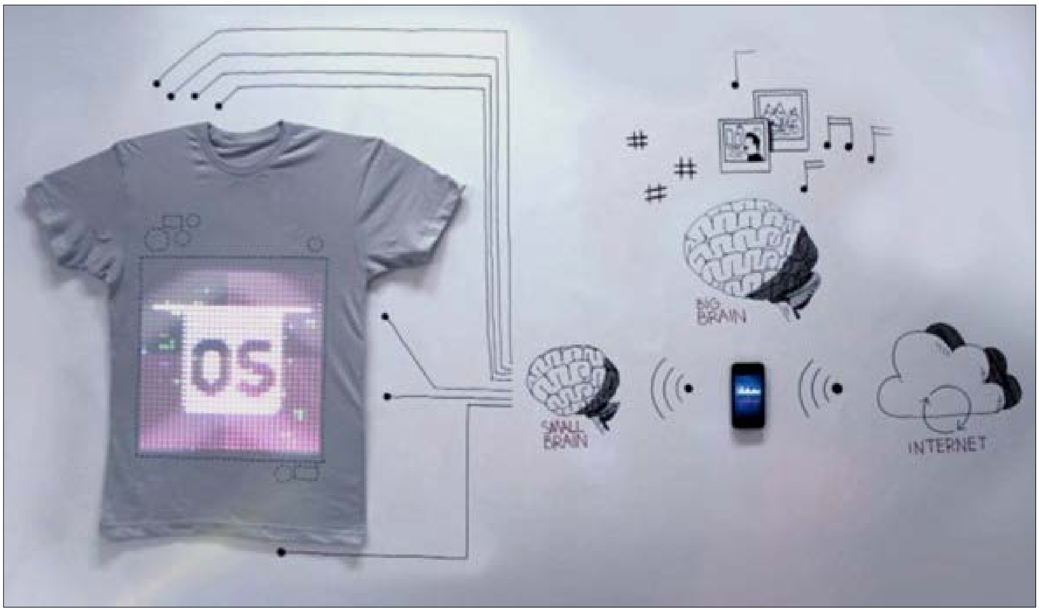
[33] http://www.3g.co.uk/PR/May2002/3315.HTM

Fig 15 photograph of a France Telecoms' fibre optic screen [31]

Alternative applications for this technology that have been suggested by the developers include advertising, the automotive industry, interior decoration and fashion.

Recently a company called CuteCircuit[34] in collaboration with alcohol brand Ballantine's[35] produced the world's first wearable and programmable t-shirt (fig 16). Via a mobile phone App the t-shirt could display facebook statuses and tweets. This is made possible by 1024 LEDs in a 32 x 32 grid.

Fig 16 an overview of the T shirt OS from CuteCircuit



[34] http://www.cutecircuit.com/tshirt-os-the-future-only-a-tweet-from-you/
[35] http://www.ballantines.com/en

2.1.12 Eleksen

Eleksen[36] was the brainchild of 2 British inventors. Chris Chapman and David Sandbach developed an electricity-conducting fabric which was called ElekTex. They were one of the first companies to have entered the wearable electronics market with a commercially available product.

The fabric is constructed by weaving conductive fibres into ordinary cloth. The Elektex fabric can be washed and ironed. It is also stated that it is durable and inexpensive to produce. A cloth keyboard (Fig 17) and a 'spongy' mobile phone that will go through the wash are 2 products that have already been developed[37].

Fig 17 photograph of a cloth keyboard [37]

This technology could also be applied elsewhere. A TV remote control could be woven into the arm of a sofa or keyboards woven into a pair of trousers or the sleeve of a jacket are all alternative possibilities.

The cloth operates in a similar way to a touch screen. Changes in conductivity are detected across the network of conducting fibres using special software and this pinpoints exactly where the pressure has been applied.

Chapman and Sandbach have developed various other prototype products in communications, medicine, sport and leisure and the automotive industry.

Their agreements with licensees prevent these products from being disclosed.

[36] Elekson is now owned by Peratech and part of the Peratech Company

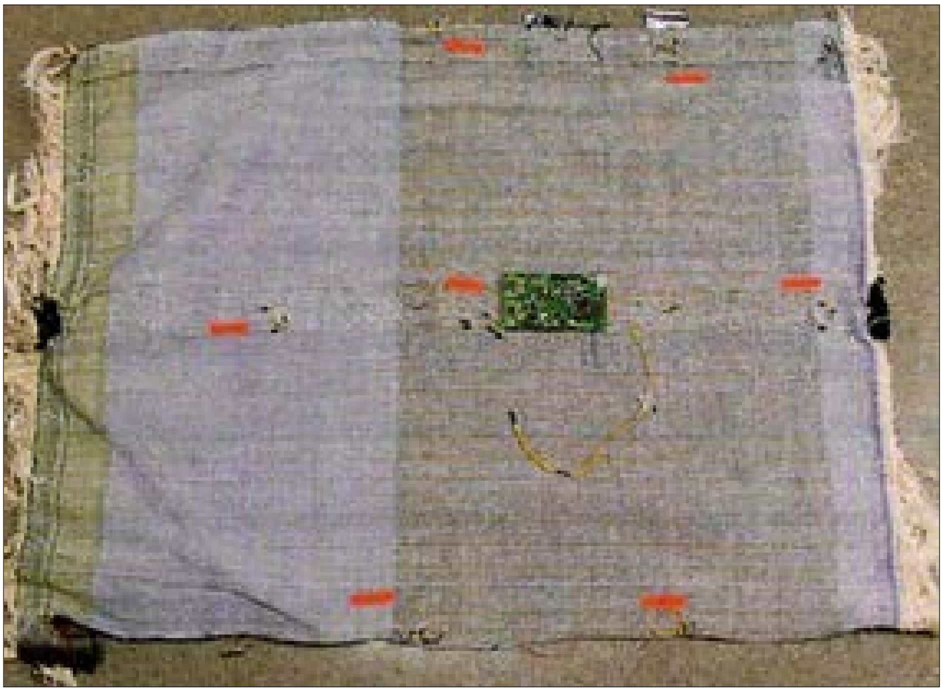
[37] More information and the range of products can be found at http://www.elektex.com/

2.1.13 Virginia Tech and the University of Southern California

The STRETCH[38] program is a development of a large E-textile (Fig 18) through collaboration between Virginia Tech and the University of Southern California. The cloth is interwoven with micro-electronic components and has a supersensitive detection array that can identify faint distant sounds.

The application was being developed for use within the battlefield to detect the sound of distant gunfire or moving vehicles. The developers also say that the cloth could be used for various applications including parachutes, tents, camouflage nets and a sail. The fabric was still in its prototype state and needed to undergo various tests before finding its way onto the battlefield

Fig 18 photograph showing a sample of E textile [38]



[38] http://www.theengineer.co.uk/news/battle-hardened-e-textiles-set-for-trials/279914.article

2.2 TEXTILE ANTENNAS

Work has been carried out at the Natick Soldier Centre, USA, to develop textile antennas to be integrated into the soldiers' battledress. This work, although linked, differs from the work carried out by other research labs due to the frequency requirements for the military.

Many establishments are investigating textile antennas to be used for medical and monitoring purposes and for use with mobile communications.

The Planar Inverted F Antenna (PIFA) has been used for many years in mobile phones and it was the PIFA that Philips proposed to use within garments (Fig 19). This is not to say though that the PIFA is the only antenna that could be integrated into textiles. There is an opportunity to challenge the findings of Philips by investigating alternative antenna designs.

In a paper titled 'Fabric antennas for mobile telephony integrated within clothing'[39] P.Massey from Philips illustrates the advantages of a wearable textile antenna.

He estimated at that point that the best mobile phones had an efficiency of 30-50% whilst the worst may be only 3-5% efficient. Massey states that the low efficiencies are due to user absorption and this could be remedied by using a fairly large conducting surface (ground plane) that separates the users' body from the radiating element.

He advises that the ground plane should be at least, preferably more than, 10cm across. It is obvious that today's mobile phones are too small to facilitate such a ground plane whereas the surface of clothing is large enough to present opportunities for integrating ground planes that would increase the efficiency of integrated mobile communications systems.

Fig 19 PIFA antenna used by Philips

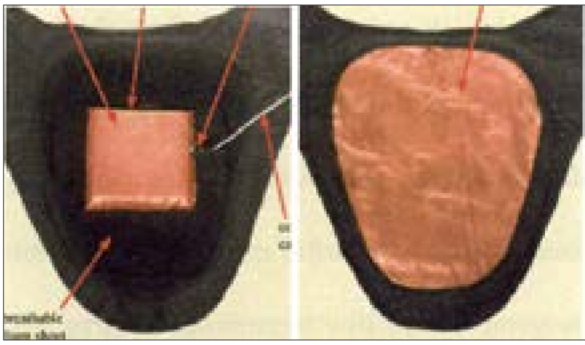
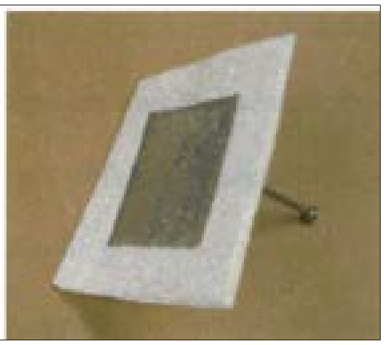


Fig 20 patch antenna developed in Zurich



The textile antenna shown in Fig 20 illustrates the prototype developed by the wearable Computing Lab, Zurich. The sample is a Bluetooth[40] patch antenna. It is said to have very good

[39] www.ee.ucl.ac.uk/lcs/paper2000/lcs030.pdf

properties such as, compatibility to Bluetooth specifications, a broad bandwidth and is made entirely of textiles.

The University of Technology in Tampere, Finland, introduced a flexible PIFA (flexPIFA) into smart clothing. No images could be found of this prototype.

A large amount of research was and still is carried out in academic institutes. The research includes the construction and development of textile antennas through to the effects of the bending of the antennas and also the effects when worn on the body. To review everything would be impossible. The following highlights some of the projects that have been undertaken.

2.2.1 Robust planar textile antenna for wireless body LANs operating in 2.45 GHz band

This project was undertaken by A. Tronquo, H. Rogier, C. Hertleer and L. Van Langenhove of Ghent University. A paper in Vol.42 No.3 of Electronics Letters in 2006 describes the antenna and its performance. The antenna was a single feed planar rectangular ring textile antenna used for wireless body LANs and would operate in the 2.4 – 2.483 GHz band.

Apart from the connector, the antenna was constructed entirely from textiles. Fleece fabric was used as antenna substrate as they state the material has 'excellent characteristics for optimal antenna efficiency'. The conducting ground plane and the antenna were both made from FlecTron fabric. This is a thin, flexible and lightweight nylon woven fabric. It is copper plated and offers high conductivity. It also offers easy handling when cutting or sewing.

The different layers were stitched together which offered them a well defined substrate thickness and also kept the antenna conformal when it was bent.

As the description shows, the antenna was constructed separately and would then be integrated into a garment, and not developed directly into the fabric like the work described in this thesis.

After testing the antenna shown to be 70% efficient when measured in-band and the antenna gain was larger than 6.5 dB.

This does prove the antenna to be successful but as a separately constructed one and then integrated and not integrated directly into the cloth at the point of production.

[40] Bluetooth, chip technology enabling connections between a wide range of devices through short range digital two-way radio

2.2.2 Design and Characterization of Purely Textile Patch Antennas

A paper was presented in Vol.29 No.3 2006 in IEEE transactions on advanced packaging by Ivo Locher, Maciej Klemm, Tünde Kirstein, and Gerhard Tröster from the wearable computing lab in Switzerland.

In the paper they described 4 purely textile patch antennas designed for Bluetooth applications in wearable computing. The frequency range was 2.4 – 2.483 GHz. They state that planar antenna structures are favoured in wearable applications as they can easily be integrated in clothing. For the ground planes and the antenna patches an electrically conductive fabric was to be used. A fabric substrate was also used which had a constant thickness and stable permittivity.

3 fabrics were chosen to take forward to the investigations, these were, a Nickel plated woven fabric, and silver plated knitted fabric and a silver-copper-Nickel plated woven fabric. The outcomes of the fabrics varied. The Nickel plated fabric was not suitable due to it being plated after the weaving process. It was discovered that the woven fibres were not entirely plated where they cross each other. This resulted in a single fibre not being continuously conductive. The silver plated knitted fabric was entirely plated polyamide fibres. An antenna constructed from this is bendable and could be integrated into clothing comfortably as the fabric elongates where necessary. They do however state a negative. Due to the elasticity of the fabric, precise shaping is a problem along with trying to assemble the antenna without it warping.

The final fabric was the silver-copper-nickel plated woven fabric. This fabric had low elasticity due to the woven structure. With the yarns being plated prior to weaving, it resulted in low electrical resistance.

They concluded that the woven fabric possessed the best electrical properties and would remain stable when assembled unlike the knitted patch antenna which would be unstable due to its elasticity.

For the textile substrate a woollen felt with a thickness of 3.5mm and a polyamide spacer fabric with a thickness of 6mm was used. The antenna was then constructed and by using adhesive sheets which were activated by ironing. This gave a thin layer of adhesive which only penetrated the surface of the conductive textile. This allowed the sheet resistance and the substrate permittivity to remain stable. Again the antenna is assembled as an additional item to then be integrated into clothing.

The results they achieved were favourable with the antenna displaying good properties and also easy to manufacture.

This does however raise questions as to how well, if at all, the antenna can be integrated into a shirt or another garment of a similar weight.

2.2.3 Textile UWB Antennas for Wireless Body Area Networks

Maciej Klemm and Gerhard Troester from the Swiss federal institute of technology presented a paper in Vol. 54 No.11 in IEEE transactions on antennas and propagation in 2006. Investigations into an Ultra wideband (UWB) textile antenna were discussed. They claimed the antennas offered a direct integration into clothing rather than being attached. This was due to the 0.5mm thickness and its flexibility.

2 antenna designs were explored, an UWB disc monopole and an UWB annular slot antenna. They were to operate in the UWB band approved by the Federal Communications Commission which is 3.1 – 10.6GHz.

For a conductor a highly conductive metalised nylon fabric was used, Nora[41]. This consists of 3 metalised layers, nickel and copper over silver. The antenna substrate was a 0.5mm acrylic fabric. They state the fact that it is light, offers good drape and remains dimensionally stable as some of the reasons for using it. Adhesive sheets were again used to fix the fabrics together. Upon testing the antennas were to agree reasonably well with the simulations. They state however that more advanced manufacturing methods would be employed in order to gain accurate repetition with the antennas.

2.2.4 High Frequency Properties of Electro-Textiles for Wearable Antenna Applications

Yuehui Ouyang and William J. Chappell of Purdue University in West Lafayette presented a paper in 2008 investigating high frequency properties of wearable antennas. Within it they explored 2 methods of integration, 1 was via weaving and the other was knitting. Their focus was looking at silver plated nylon yarns and thin silver plated copper yarns. One of the yarns they used was X-Static. The same yarn that was used in the Authors experiments.

As with the work presented in this thesis, Ouyang and Chappell created samples using the conductive yarn in only one direction with a non conductive yarn in the other. They state that the arrangement of conductive and non conductive adds to the wearable feel of the fabric. This was one of the aims of the author; the fabric antenna should retain a natural and wearable feel.

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[41] http://www.shieldextrading.net/pdfs/Nora.pdf

The woven and knitted fabric both used the same X-Static yarn. They found that the woven structure was more efficient in terms of electrical conduction. This was due to the conductive paths being better aligned with the current directions. The knitted fabric with the interleaving structure had conductive paths in all directions. This wasn't a uniform pattern in all directions which lead to the construction being lossy.

The tests were also carried out with the construction of a conductive fabric. Differing types of Satin weave were investigated. Satin weave is applied to fabrics with asymmetrical patterns on each side. The interweaving ratio of the vertical and horizontal threads is 4:1 and the weave pattern is periodic every 5 threads. This pattern is called Satin 5. This is the one that was used in their tests.

On the face side of the fabric, more vertical non conductive threads than conductive horizontal ones are visible. On the reverse, which is the metallic face, more conductive than non conductive threads are visible. This lead to both sides of the fabric being tested to see which face would sit against the substrate.

2 fabric patch antennas were constructed and tested. With the fabric face downwards to the substrate the efficiency was 79%. This rose to 88% when the metallic face was placed downwards.

A final fully fabric antenna was fabricated at 2.44GHz using the same woven fabric for the ground plane and the top patch. 8 layers of polyester fabric were stacked and used as an insulation layer. This was around 4mm in thickness.

The tests indicate that the measured radiating patterns match well with the simulated ones. The measured gain of the antenna at 2.44GHz is 6.6dB. They stated that this antenna can be used in smart clothing for WLAN communications with moderate antenna gain and impedance bandwidth larger than 4%.

2.2.5 Patria

One of the main research laboratories to publish their findings is Patria. Patria is based in Finland and its official title is Patria Aviation Oy[42]. They were supported by the European Space Agency and Oulu University in Finland was used as a subcontractor for the project.

The work that Patria carried out was the complete design package and process. This was substrate material selection and characterization, through to design implementation and verification of a textile antenna (fig 21 and 22).

The overall objective of the project was to study and analyze the viability of the textile/flexible substrates available for antenna elements and arrays but more specifically, demonstrate compliance with satellite antenna user requirements using these flexible/textile substrates.

The antenna was to be operated via the Iridium satellite phone system. The Iridium satellites operate at low altitudes (LEO, low earth orbit). This enables communication between satellite and end user without the need for huge antennas. Iridium satellites also allow for two-way voice and data communication. The antenna developed may also be used in combination with the GPS satellite system where positional data can be relayed to the user and Iridium could relay the position of the user to operational centres.

The selected application defined the antennas polarization; this was to be polarized circularly. With using the Iridium satellite phone system, the operational frequency band is the L-band or Iridium band.

The antenna was considered to be self conformal. Basically this means that with the antenna being flexible/textile, it can adapt its form according to where the antenna may be attached. This is a very important factor to consider with flexible antennas. Is performance compromised when the user bends and moves? Patria have managed to maintain radio signal under the test conditions as the antennas geometry allows it to bend in a way that doesn't reduce performance.

No evidence could be found as to whether the antenna could be handled for life testing. Can it be ironed, washed, and if so what temperature? Whether these questions were addressed is unknown.

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[42] http://www.patria.fi/patria_www_en_sisalto/patria_www_en.html

Fig 21 Image showing wearable fabric antenna from Patria [42]

Fig 22 Image showing fabric antenna attached to a jacket [42]

The image clearly illustrates one thing. As with other textile antennas that have been looked at within this document and also during the research carried out for this thesis, the Patria antenna is still not completely integrated. The investigations and experimentations discussed within this written piece were to see if it were possible to introduce an antenna at the point of production so that it was truly an integrated antenna. The accompanying image shows the antenna stitched on to the arm of a jacket.

This method highlights again the type of garment to have a wearable antenna is possibly limited due to the weight and thickness of the antenna. Can this only be used with a heavier weight fabric? How would it sit on a lighter weight fabric, for example, a polyester/cotton shirt? The Authors main intention was to investigate a textile antenna that was fully integrated into a garment or cloth. As yet, there is still no evidence that this has been possible.

2.2.6 GHENT UNIVERSITY

Ghent University in Belgium has participated in a number of investigations involving the development of wearable antennas and smart textiles. The following section illustrates briefly one of the projects.

2.2.6.1Proetex

Proetex (PROtection E-TEXtiles) was an integrated project that concentrated on the development of e-textiles which were to be used in wearable textile systems for emergency disaster personnel and injured civilians[43].

The extent of these projects is such, that 23 partners from 8 different countries were involved. They included representatives from some of the most important European textile regions, Italy, France, Poland and Belgium.

The project was aimed at developing textile-based systems that would increase both the safety and efficiency of emergency personnel who would attend such disasters as earthquakes, fires, floods and terrorist attacks. With this is mind it is imperative that whatever system is developed, has to be infallible in terms of communication and protection.

With such information required it would be impossible to integrate all of the required elements into one garment. Therefore multiple projects and garments were required. Vital body signs would be monitored via a garment close to the skin. Other sensors would need to collect data from the wearer's environment, therefore an inner and outer garment was produced and also the boots were part of the wearable system.

Along with this, a patch was to be developed for the victim to wear which would monitor their health condition.

To summarise the multi functional garment, the image from the Proetex website[44] (Fig 23 overleaf), is said to offer the following advantages:

Continuous monitoring of body signals e.g. respiration and heart rate;

Activity monitoring;

Internal and external temperature monitoring;

Wireless communication;

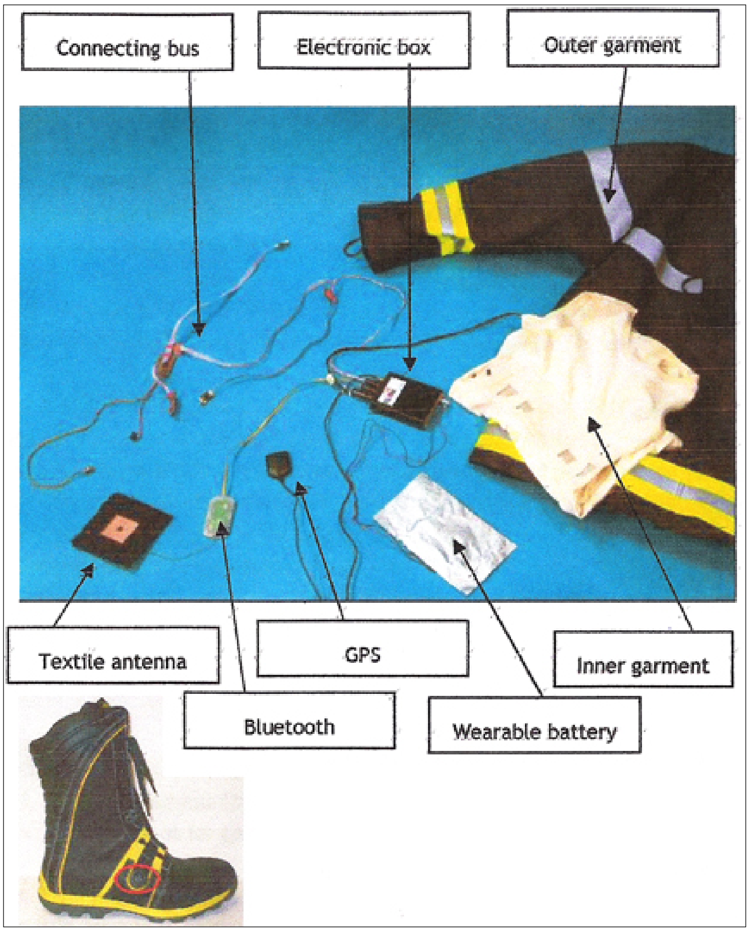
Chemical detection;

[43] http://www.ugent.be/ea/textiles/en/projects/Lopende%20projecten/proetex.htm

[44] http://www.proetex.org/final%20proetex%20learning/firefighters.htm

Energy supply;

Fig 23 Image showing all the components used in the Proetex project [44]



A presentation was given at the Third Nordic Smart Textile Network Meeting in Oslo 2009 which gave greater detail of the research carried out with the Proetex project.[45]

Along with the other work, Ghent University investigated the coating of yarns and fabrics with precious metals, including gold, which would improve the quality of the textile electrodes to be integrated into the inner garment. The communication between the inner and outer garment was established by a textile antenna.

The investigation into the textile antenna was in relation to this project and also a project titled ‘Data transmission and wireless communications for smart textiles’.

Figure 24, overleaf, shows a textile antenna integrated into the collar of the coat.

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[45] www.sintef.no/project/pHealth2009/.../SmartTextiles_Bonfiglio.pdf

Fig 24 Image showing integrated textile antenna within the collar of a coat [45]

With this, they investigated the conversion of a micro strip patch antenna into a textile. This was to consist of multi layer structures combining electro textiles for radiating the patch and a ground plane and conventional non-conductive textile material for antenna substrate. With any project such as this, the electromagnetic properties of the substrate material are crucial. Also the behaviour of the antenna when influenced by such things such as bending, moisture content and the close proximity of the body is another huge factor to consider. A ground plane can be added to help shield the body from the antenna. They also looked at the feeding structures. This is how the antenna is connected to the transceiver, which feeds the antenna. This was also investigated during these investigations in the way of transmission lines.

2.2.7 University of Sheffield

The University of Sheffield have investigated a wearable textile antenna but rather than integrated into clothing, this was to be worn against the body. It is constructed from common clothing fabrics and is operational within the 2.45 and 5GHz wireless bands, which is for network communications[46].

The materials used were felts, cloth and leather. No more information was available to establish what the cloth was. Another fabric used was a conductive woven fabric called 'Zelt'[47]. Due to its close proximity with the body, the antenna was constructed with an Electromagnetic band-gap (EBG) material to act as a high-impedance surface (HIS) which would reduce back radiation from the antenna and make it more tolerant to positioning on the body.

The prototype antenna was constructed using hand cut pieces of fabric layered up. The base layer being a thin felt at 1.1mm thick. The other components were either stitched or attached using a thin layer of adhesive. Further prototypes were constructed using laser cut elements. Their findings indicated that there were no significant differences between hand cut elements and laser cut elements. The test procedure also involved testing the antenna for wearable performance. Once it was flexed out of its normal resting state, how did it perform? Their findings were encouraging.

Further research has been carried out on the performance of the antenna when it is crumpled. Again this investigation shows that although it is a textile antenna, it still is not an integrated antenna[48].

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[46] eprints.whiterose.ac.uk/8603/2/Zhu_published(IEEE).pdf

[47] More information can be found at http://responsivetextiles.mica.edu/node/244

[48] proceedings.metamorphose-vi.org/.../01_Langley-20090312-034820.BendingIntegratedEBGantenna.pdf

2.2.8 Swiss Federal Institute of Technology

In 2010 the Swiss Federal Institute of Technology released a paper titled 'Woven Electronic Textiles: An enabling technology for health care monitoring in clothing[49]'.

Within the research they investigated the integration of electronic devices into a textile at the yarn level. They were exploring the integration of sensors into a textile band, which when combined with an undershirt (Fig 25), could measure the temperature between the skin and clothing.

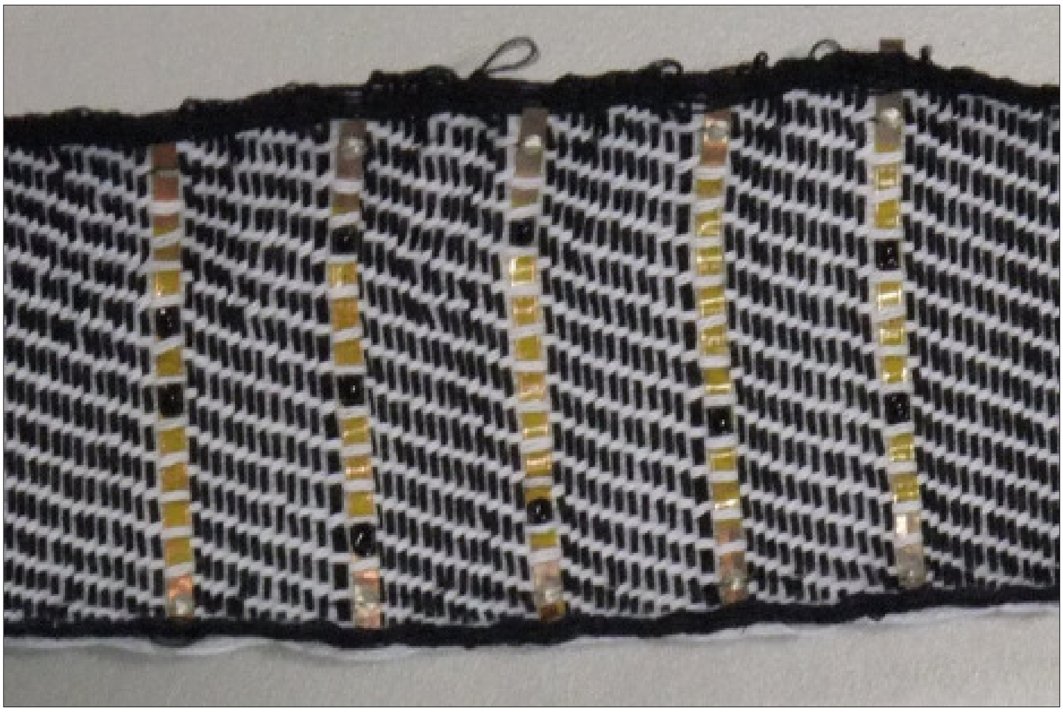
This monitoring would be for people who work in high risk professions, athletes and dementia patients who could be at risk from a high body temperature.

Fig 25 photograph of the undershirt with integrated textile band

For the experiments, conductive yarns were integrated in the warp direction and flexible plastic fibres which had integrated electronic functionalities were introduced in the weft direction. This is shown in the image of the woven fabric sample, (Fig 26).

[49] www.create-net.org/.../ubihealth/.../Zysset_Woven_Electronic_Textiles.pdf

Fig 26 photograph of conductive yarn and plastic fibres integrated into a woven fabric



The reason for having conductive yarns in the warp was to connect the electronic circuits on the plastic fibres.

The results indicate that for the most part the performance from the fabric when flexed, and when under pressure remain stable. However, when the tape is flexed and becomes in contact with itself there are error signals in the sensors.

This can be overcome by using insulated conductive yarns.

For more information regarding the projects undertaken it is advised to visit the wearable computing lab[50] division within the establishment.

2.2.9 PSG College of Technology

The PSG college of Technology[51] in India is also investigating the use of smart/electro textiles. P.Kandhavadivu, C.Vigneswaran and Dr. T.Ramachandran released a paper in 2010 titled 'Application of woven antenna in wireless communication device integrated apparel and bed linen'[52]

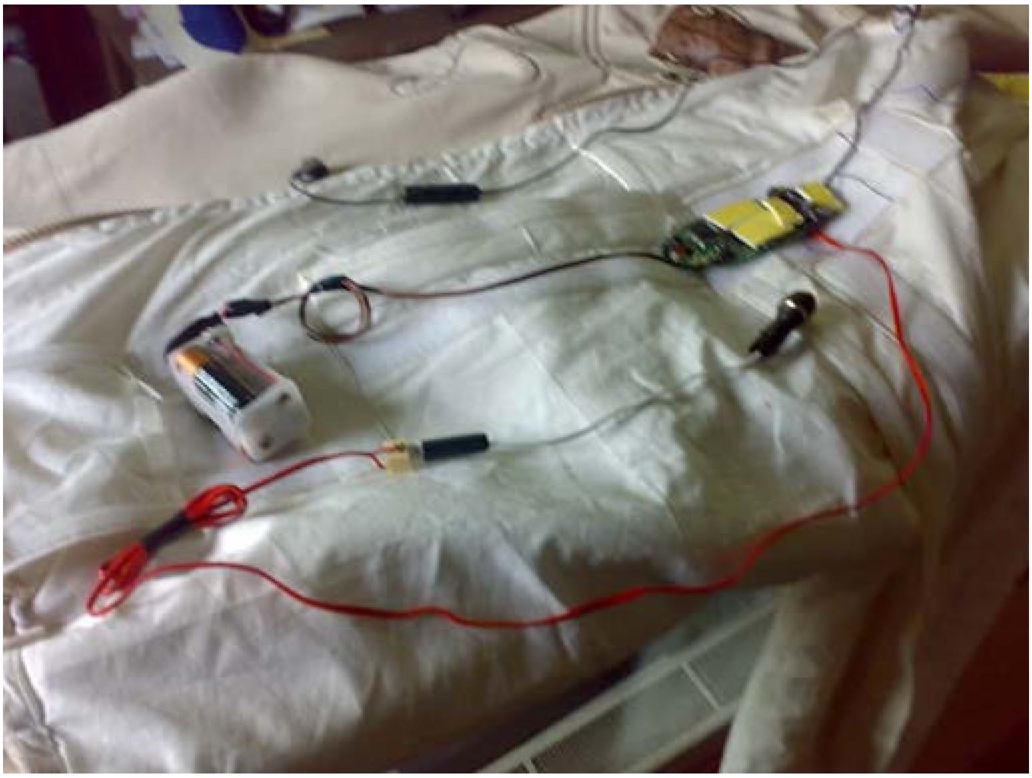
[50] http://www.wearable.ethz.ch/
[51] http://www.psgtech.edu/
[52] www.ijest.info/docs/IJEST10-02-10-123.pdf

Within the project they investigated the integration of electronics into apparels for communication purposes. For this they explored a wireless communication device, silicon based micro-machined transceiver and a concept fabric antenna for transmitting and receiving radio signals Fig 27.

The aim of the research was to identify and simplify a means of communication between people within the same surroundings.

Suggested end users for this technology were those confined to a wheel chair or bed ridden, defence, construction and police personnel.

Fig 27 photograph shows a jacket produced at PSG with the integrated components



The paper concludes by stating that many electronic devices require the user to have some user skills.

Their concept was to allow the interfaces to be more user friendly by simplifying the way in which the systems were operated. This would enable those whose mobility was impaired to communicate with carers more easily.

The Author is aware that during the time elapsed since completing his practical work with textile antennas; other research laboratories have been continuing to investigate this complex area and publishing their findings.

The following sections highlight what developments are being made and varying methods in how these experimentations are being conducted.

2.2.10 National Textile Centre Research

The new 'buzzword' that is being used is that of 'Plastic Electronics'. The section written on Plastic Electronics covers the investigations that are being carried out. One research laboratory working within this field is the National Textile Centre Research dept[53]. The centre has also investigated the potential development of a flexible/wearable antenna. They have however, approached this in a different way to other research laboratories.

Their aim was to look at the patterning of carbon nano tube conducting polymer based electronic ink on a textile substrate. It would be by controlled micro-droplet deposition and would be printed onto the fabric in the design of the antenna and antenna arrays which are in the microwave and millimetre wave frequency range.

Previously the Author had experimented with a flexible conductive ink which was originally developed for use on neoprene diving suits. The initial results from the Authors findings were encouraging with the simple experiments that were carried out.

It was interesting to find other laboratories that were now considering the use of conductive inks.

The textile research centre had been investigating the properties of the ink and highlighted the need to find a highly conducting nanotube based alternative to silver for RFIDs[54]. Obviously there is more to this than simply printing with an ink. Was the first mixture correct? Are the particles mixed sufficiently to have a uniform coating? Several ink formations were developed for use.

The tests that they carried out were done by using an inkjet printer. The CNT conducting polymer electronic ink was printed onto a flexible textile substrate. The advantage of using the carbon nano inks was that they gave sufficient flexibility, weight and conformity.

A polymer based wearable microstrip antenna was prototyped by the Centre. Not a great deal of information was available regarding the test results of the antennas but they did state some findings.

CNT based electronic ink has enough threshold conductivity to be used a conductor for a patch antenna.

[53] http://www.ntcresearch.org/current/FY2010/FY2010_proj.htm

[54] Radio Frequency Identification

If the ground plane has sufficient dimensions, the amount of radiation that could be absorbed by the human body wouldn't reach a critical limit and also human antenna interaction wouldn't play a significant role on antenna performance.

Lastly, they stated that conductor inks would have to be developed in order to provide sufficient durability.

The use of standard inkjet printers opens up great potential in the development of wearable antennas. The move forward from traditional methods could speed up the process dramatically but as there are no concrete results as yet, development of such new practices is paramount.

This does however move away from the initial idea of a fully integrated antenna but in terms of idea development, the printed design of the antenna could be integrated with a printed pattern on a garment or piece of cloth.

2.3 RESEARCH THROUGH COLLABORATION

Whilst researching this particular area, one word that will continually appear is 'collaboration'. Multi discipline collaborations are a prerequisite to enable successful development of products. Electrical engineers, computer scientists, textile technologists and fashion designers all working together to develop electro-textile garments or fabrics.

With these collaborative working methods come difficulties. A barrier is automatically in place as the textile industry has a totally different way of working and also different terminology to that used by electrical engineers and computer scientists. However, this difference in working procedures and practices also has its benefits.

Through previous experience it is evident to the author that there is a difference in the way that electrical engineers think, compared to that of a textile/fashion designer. What could be perceived as a negative is quite the opposite. Through these differences innovative products can emerge.

In previous work the Author collaborated with electrical engineers and was aware that applications that were never thought of could emerge with having brainstorming sessions with those from another discipline.

The importance of the multi discipline collaboration was recognised as he worked alongside electrical engineers. It would be impossible to undertake the enormity of the project without the correct knowledge of the specific areas that were to be involved. With having a textiles background, it would be impossible to have all of the required information regarding microwave circuitry to successfully achieve an outcome. This is where the collaboration with electrical engineers in vital.

In June 2004 a conference was held in Leeds titled "Wearable Electronic and Smart Textiles". Paul Gough from Philips Research Laboratory gave a paper titled "Electronics and Clothes: Watt to Wear"[55].

Within the paper he outlined his observations that were made during the original collaboration between Philips and Levis in the production of the ICD+ jacket that was mentioned previously.

Gough stated that communication was an issue. Development processes, timescales and the approach to the market and the language used were also highlighted.

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[55] Document available at www.smarttextiles.info/ members download area

Timescales used within the fashion industry are seasonal, these are 6 monthly innovations. Gough commented that the electronics companies, who need considerably longer for any fundamental innovation, couldn't meet this turnaround. He suggested a solution to the problem was to take a platform approach, which is what apparently happens with mobile phones and MP3 players. This means that the core electronics can stay the same for a number of seasons but various new features could then be added on a seasonal basis.

Another observed problem, and this could possibly apply to most companies dealing with electro textile garments, is the level of investment. Gough stated that it can take millions of dollars to produce a suitable platform for a garment. This would be considerably higher than the cost of a range of clothing. To recover the costs he suggested that the platform would have to be applicable to a broad range of garment markets.

Despite these problems, Paul Gough remained confident that the collaborations are successful and fundamental for the growth of electro-textiles.

3 PRACTICAL EXPERIMENTS

The initial practical experiments that were in carried out during the first year of the investigations were informed by the literature review. It was evident that a good electrically conductive fabric would be important to achieving successful outcomes.

At the point of the initial experiments there was very little information regarding textile antennas. Due to the sensitive nature of the research area, relevant information regarding materials that were being used in the construction of textile antennas was difficult to obtain, if at all.

No bench mark was available to work to as the prototypes displayed by other research laboratories were constructed with textiles but were not totally integrated.

The absence of information put more emphasis on the practical experiments in order to answer one of the initial research questions.

'Is it possible to produce good quality conductors in a range of fabrics?'

Prior to weaving the conductive fabric samples, it was important to identify the most successful woven structure which could facilitate an antenna.

3.1 Identifying Structure

It was important for this research to understand some of the various structures used in weaving in order to see if or how conductive wires may be integrated. The samples would offer an understanding as to the strongest or loosest woven structure and inform decisions as to which would potentially, be the most successful in terms of integrating an additional yarn when constructing an antenna.

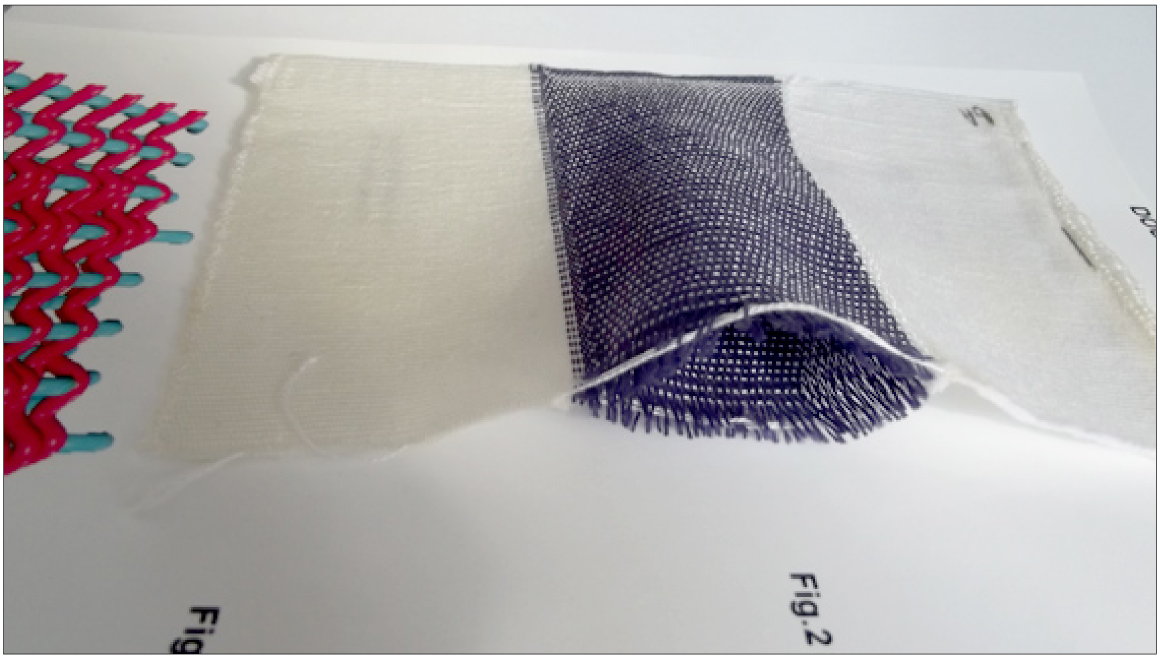
In total, 18 sample structures were woven. Each structure was woven with 3 different warp yarns which would allow drape and handle to be assessed. The warp yarns were a 2/20s cotton, 2/28 polyester and 16/2 Tencel. For all samples Tencel was used as the weft yarn. As the samples were being woven only to identify structure, no importance of weft yarn was considered.

All samples were woven at 10 ends per dent using a 4 spreader. A spreader is tool on the loom that separates the warp yarns and also allows for a straight selvedge. The gaps in the spreader are called dents. There are various sizes available. A 4 spreader means that there are 4 dents per inch. If in this case there are 10 yarn ends per dent. In total this equates to 40 warp yarns per inch. The more ends per inch the finer the fabric.

The warp yarns were chosen as they are a very common yarn used widely in the production of textiles. Cotton is a natural yarn and opposite to that is polyester which is a man made yarn. Tencel was used as it is a relatively new yarn and possesses characteristics that allow it drape well and resist wrinkles.

Along with single cloth samples, double cloth was also investigated. This structure can give 2 face sides to a fabric and also allow pockets to be woven for possible encapsulation of components FIG 28.

Fig 28 photograph of a double cloth showing the pocket which could be used for encapsulating components, Authors own image



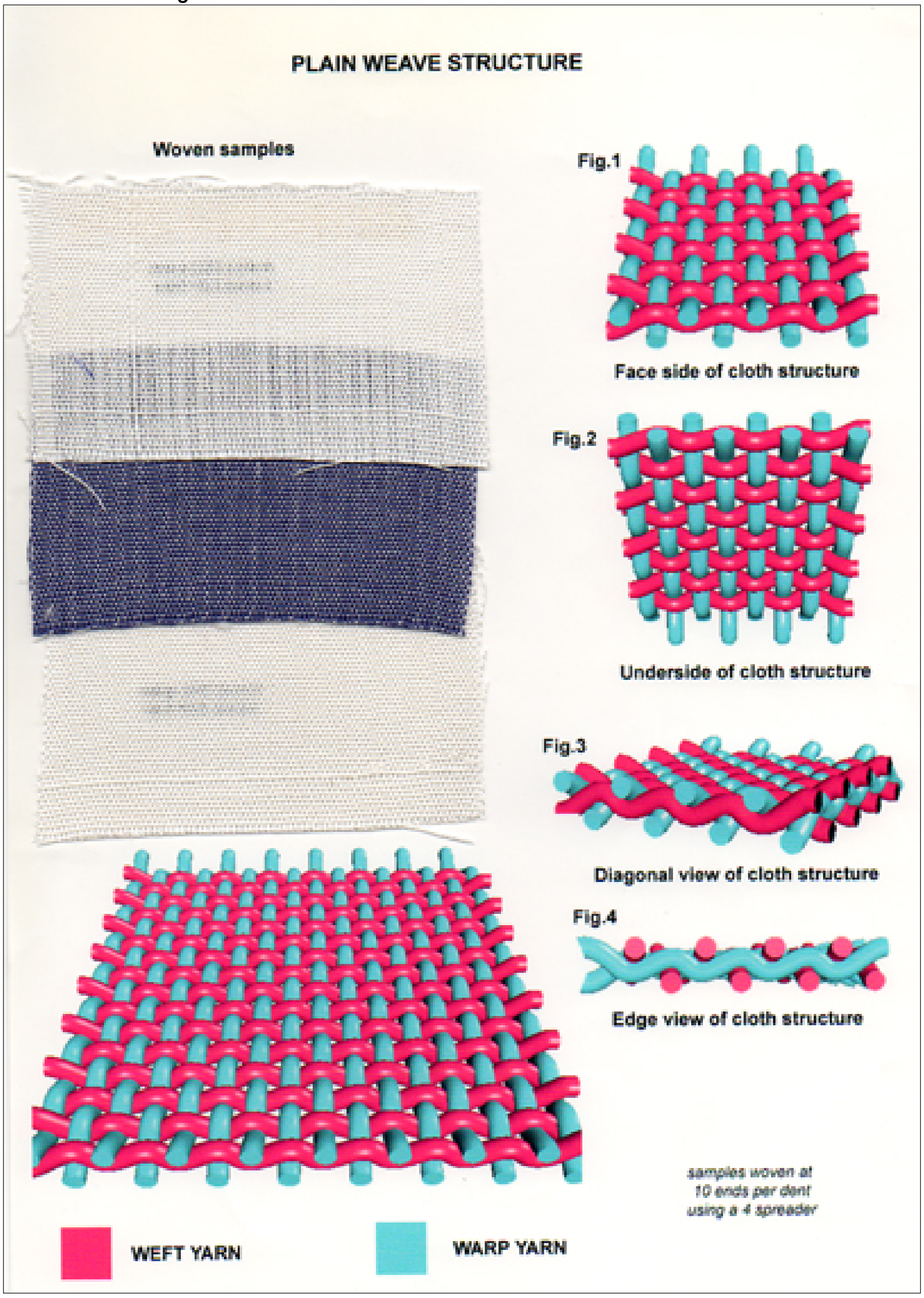
Although this woven structure was never taken any further in the investigation, the initial idea would be that the pocket could potentially house the power supply, in the form of a battery.

To gain a greater understanding of the woven structures, the Scotweave computer program[56] was used alongside the woven samples. The program allows the lifting plan of the structure to be entered which then enables a 3 dimensional view to be studied. See fig 29.

This allows the user to view exactly which warp yarns the weft is passing over or under.

[56] A computer aided design package that works in relation to the electronic jacquard weaving machine

Fig 29 image showing illustrations taken from the Scotweave program along with actual woven samples Authors own image

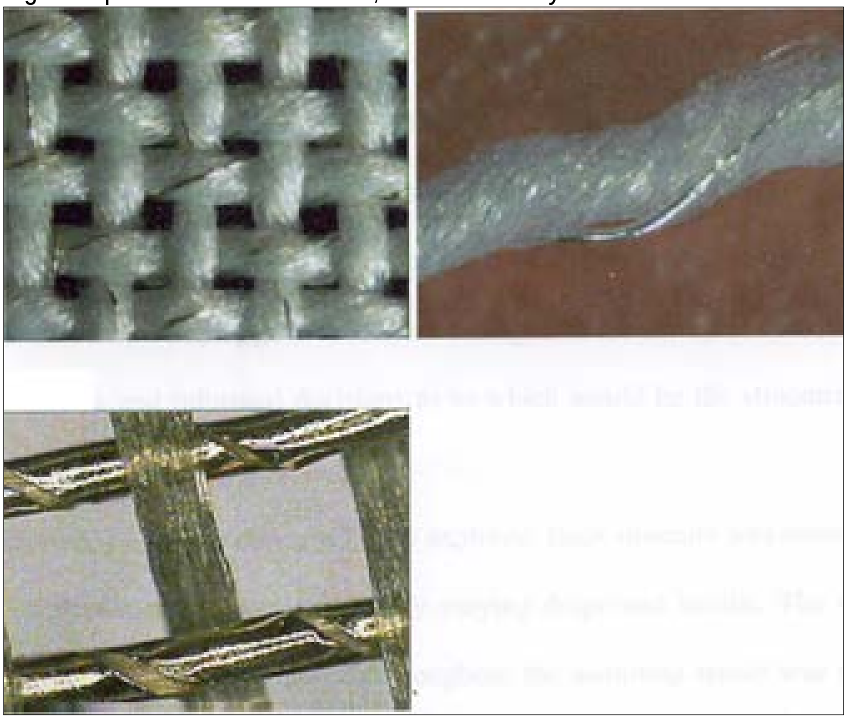


Through the production of the woven samples and using the Scotweave program, it was ascertained that the Plain weave structure would be the most successful to use with the integration of an antenna. The plain weave gave a strong cloth; this is due to the weft yarn going over and under only one warp yarn at a time. This structure would also allow a conductive yarn used in the weft to sit close with itself which in turn would give a condensed area of conductivity.

3.2 INITIAL CONDUCTIVE YARN SAMPLES

Various conductive yarn samples were explored by the Author. Conductive yarns that had been used during work at MIT and the Wearable Computer LAB (fig 30) had initially informed these investigations. They had used fine wires with yarns.

Fig 30 Images of conductive yarns, the top 2 used by the wearable computing lab, shows a polyester yarn twisted with a metal fibre. The fibre is insulated to prevent short circuiting. The other image shows a silk organza spun with a metallic thread, this was used by MIT.



The images from the wearable computing lab (Fig 30) illustrate 2 different types of yarn that have had conductive elements introduced. The polyester yarn twisted with a metal fibre as a single strand and also when it has been woven in a group. The yarn was insulated in order to prevent short-circuiting. This yarn was used in experiments conducted by the Wearable Computing Lab, ETH Zurich[57].

The other yarn shows a yarn that was used by MIT[58] for their investigations. The silk organza yarn has been spun with a conductive metal thread.

The introduction of a fine wire into an existing yarn was explored.

The wires used were, 0.05mm tinned copper wire, 0.10mm tinned copper wire, 0.08mm stainless steel wire and 0.1mm stainless steel wire.

[57] www.wearable.ethz.ch

[58] http:/web.media.mit.edu/~rehmi/fabric/

The yarns that the wires were spun with also varied. They included Dupion Silk, Worsted Lambs wool, Cotton, Tencel, Worsted wool crepe and polypropylene. The yarns also varied in weight. The full list of yarns spun and used can be seen in the results table.
One of the aims of the project was to produce antennas in various weights of fabric. The yarns chosen give a broad range of possibilities. If successful spinning of the various yarns with wires was achieved it could allow for the integration of antennas in year round apparel.

3.3 SPINNING PROCEDURE

The method of spinning the yarns was unorthodox. Each sample yarn was 5m in length with an equal length of wire spun with it. The length of yarn was attached to a fixed object; in this case it was a weaving implement known as a 'comb'[59]. Opposite to the fixed end, a loop was tied in the yarn and then attached to a hook that was secured in the chuck of a cordless drill. The fine wire was attached to the same fixed point. Again a loop was tied at the end and attached to the same hook. The yarn and wire were stretched to their full length and the cordless drill was operated.
The wire and yarn were spun together under tension in a clockwise direction for 4 minutes at the drills stated maximum revolutions per minute (rpm), which was 400 rpm. This gave an approximate number of 1600 twists in the yarn. The time of 4 minutes was used as multiplied by the stated RPM, 1600 twists in the yarn would seem an adequate amount of twists for the wire and yarn to hold together.
Once the time had elapsed the wire and yarn were taken off of the hook and the tension was then relaxed. Once the yarn and wire were no longer lively, it was ready for use.
This method was used for twisting the single length of yarn and wire.
For the samples that consisted of 2 lengths of yarn and wire, a similar method was used.

After following the same procedure as before, with the same lengths of wire and yarn and spun for the same amount of time and RPM, the sample yarn was attached to a fixed object under tension. An additional yarn was then introduced.
A second 5m length of yarn was fixed to the same point, the comb, and again attached to the hook in the cordless drill.

[59] An implement used in dressing the loom to aid in the spreading of the warp

On this occasion the length of yarn was spun by itself under tension, in a clockwise direction at again the maximum stated RPM which was 400, but for only 2 minutes. This gave an approximate number of 800 twists in the yarn. The previously twisted wire and yarn were then attached back on to the hook with the single yarn and they were twisted together in an anti-clockwise direction for approximately 30 seconds. Once the time had elapsed the tension on the yarns was released and relaxed which allowed the yarn to rest. Once the yarn was no longer lively it was ready to weave.

It was hoped that the process of twisting in a clockwise and anti clockwise direction would twist the yarns sufficiently so they held together when used for weaving.

The work was experimental and unorthodox but the initial woven samples would prove if this method was successful or not.

This method was used for all of the yarn samples produced.

The newly spun conductive yarns would be used to weave a small sample of conductive fabric. This would then give an indication as to whether the yarn would be suitable for use when considering the construction of a fabric antenna.

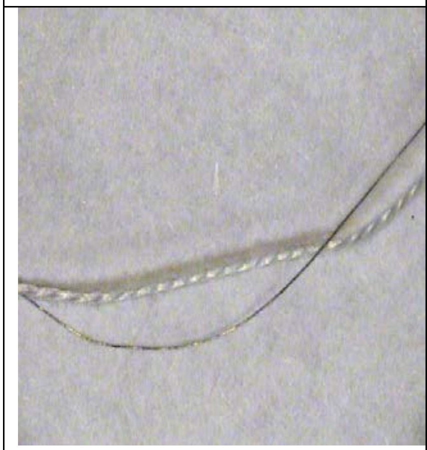
3.4 INITIAL CONDUCTIVE FABRIC SAMPLES

The conductive fabric samples that were produced were done so using the existing 3 warp yarns used for the initial structure samples, cotton, polyester and Tencel. The previously used Tencel weft was replaced by the 5m sample lengths of twisted wire and yarn. The conductive yarn was woven across the 3 warp yarns in order to investigate the different feel and drape of the wire integrated into yarns used in textile apparel manufacturing (fig 31).

Fig 31 woven sample showing the 3 sections of cloth, on the left is the cotton, central is the polyester and on the right is the tencel

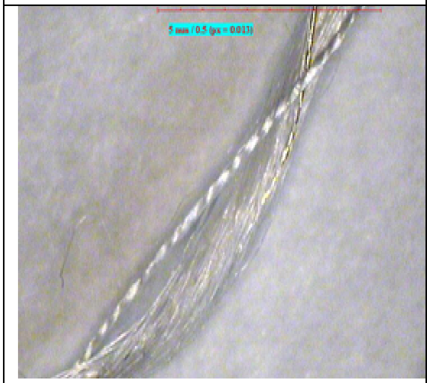
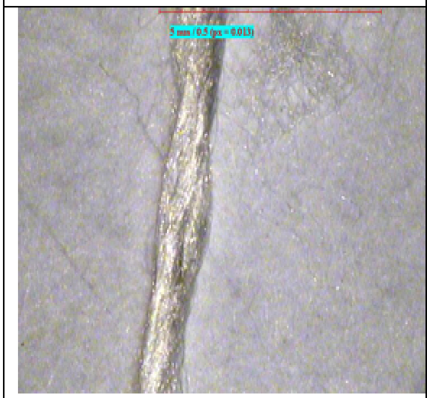
The following tables present the information from the samples that were woven

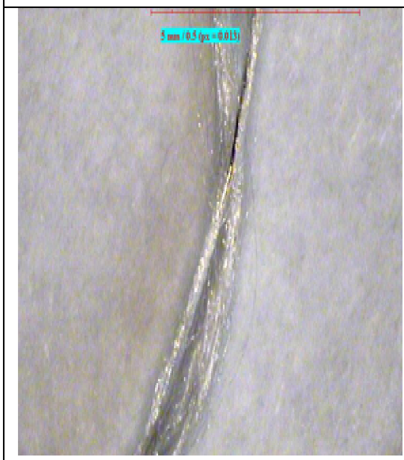
Yarn Image	Yarn used	Supplier	Conductive properties of yarn and length of yarn tested	Characteristics of yarn Once woven
	2 lengths of 2/20s cotton and 1 length of 0.08mm stainless Steele wire.	Authors own sample	13.2 Ohms Length of yarn tested 12cm.	A lack of flexibility is apparent as the woven sample remains in a flexed state. The cloth also has a textural feel to it due to the wire used.
	1 length of 2/20s cotton and 1 length of 0.08 stainless Steele wire.	Authors own sample	13.3 Ohms Length of yarn tested 12cm	The yarn and wire didn't twist very well. This resulted in loops of wire being visible through the surface of the cloth. Poor flexibility was again experienced with the cloth remaining in a flexed state.

Yarn image	Yarn Used	Supplier	Conductive properties of yarn and length of yarn tested	Characteristics of yarn Once woven
	2 lengths of 2/60s Cotton and 2 lengths of 0.05mm tinned copper wire	Authors own sample	1.0 Ohms Length of yarn tested 20cm	The wire twisted well with the yarn and was barely visible in the woven cloth. Flexibility was reasonable although it remained in a slightly flexed state. The texture of the cloth was good and the wire could not be detected by touch.
	1 length of 2/60s Cotton and 1 length of 0.05mm tinned copper wire	Authors own sample	1.2 Ohms Length of yarn tested 8.5cm	The wire didn't twist too well with the yarn but this wasn't noticeable once it was woven. Reasonable amount of flex in the cloth with minimum stiffness once flexed. The cloth texture was good to the touch.

Yarn image	Yarn Used	Supplier	Conductive properties of yarn and length of yarn tested	Characteristics of yarn Once woven
	2 lengths of 2/60s Cotton and1 length of 0.05mm tinned copper wire	Authors own sample	23.1 Ohms Length of yarn tested 20cm	The wire is protruding from the front and the back face of the cloth in some areas when woven with cotton and the tencel. It was more successful when used with the polyester. Flexibility is poor with the cloth remaining in a flexed state once handled.
	2 lengths of 16/2 Tencel and 1 length of 0.10mm tinned Copper wire.	Authors own sample	00.3 Ohms Length of yarn tested 16cm	The wire and Tencel held together well once twisted. Once woven the wire cannot be detected in the cloth but there is a noticeable stiffness to it. The cloth remains in a flexed state once handled.

Yarn image	Yarn Used	Supplier	Conductive properties of yarn and length of yarn tested	Characteristics of yarn Once woven
	1 length of 16/2 Tencel, 1 length of 2/60 cotton and 2 Lengths of 0.05mm Tinned copper wire	Authors own sample	00.5 Ohms Length of yarn tested 21cm	Overall appearance of the yarn is good as the wire and yarns appear to have twisted together well. Once woven there are no visible signs of the wire although flexibility is an issue. The fabric sample remains in a flexed state once handled.
	1 length of 1/27 Worsted wool Crepe, 1 length of 2/60 cotton and 1 length of 0.10mm Tinned copper wire	Authors own sample	00.2 Ohms Length of yarn tested 10cm	The yarn and the wire haven't twisted very well together giving a very untidy appearance. Once woven there are many small loops of wire visible on the face and the rear of the fabric samples. Flexibility issues are again apparent as the fabric remains flexed once handled.

Yarn image	Yarn Used	Supplier	Conductive properties of yarn and length of yarn tested	Characteristics of yarn Once woven
	1 length of Polypropylene, 1 length Of 2/60 cotton and 1 Length of 0.08 Stainless steel wire	Authors own sample	23.2 Ohms Length of yarn tested 20cm	The yarn hasn't twisted together very well. Once woven, tiny loops of wire were again visible on the face of the fabric. Flexibility issues were again a problem with the fabric sample remaining flexed once handled.
	2 lengths of Dupion silk and 2 lengths of 0.05mm Tinned copper wire	Authors own sample	3.08 Ohms Length of yarn tested 21cm	The yarn held together well with the wires being well mixed with the silk. Once woven, the wires were not noticeable and the flexibility of the cloth sample was good and it retained a reasonably soft feel.

Yarn image	Yarn Used	Supplier	Conductive properties of yarn and length of yarn tested	Characteristics of yarn Once woven
	2 lengths of Dupion silk and 4 Lengths of 0.05mm Tinned copper wire	Authors own sample	3.8 Ohms Length of yarn tested 8cm	The yarn didn't twist together as well as the previous sample. Once woven the fabric sample felt good to the touch but flexing issues were again apparent as the fabric remained in a semi flexed state once handled.
	2 lengths of dupion silk and 1 length of 0.1mm stainless steel wire	Authors own sample	22.8 Ohms Length of yarn tested 22cm	The thickness of the yarn didn't lend itself to twisting with the silk. Although looking crude, the yarn wove well and the feel of the fabric sample was good. Flexibility issues again arose as the sample remained flexed once handled.

Yarn image	Yarn Used	Supplier	Conductive properties of yarn and length of yarn tested	Characteristics of yarn Once woven
	2/52 lambs wool and 2 lengths of 0.05mm tinned copper wire	Authors own sample	01.3 Ohms Length of yarn tested 15cm	The wire and the wool held together well once twisted. When woven the cloth sample had a good feel to the touch and flexing issues were not as bad as previously experienced although the sample did remain in a semi flexed state once handled.

The findings on the most part were not encouraging. Many of the samples were rigid and lost a great deal of their original textile qualities in terms of feel and drape.

Although the appearance of a few of the samples looked and felt acceptable, the fragility of the wires used in them would render them unacceptable for use. After several times of flexing the finer wires, in particular the 0.05mm tinned copper wire, could fracture and through this, would lose the constant conductivity, which is required to ensure the smooth operation of any electronic function that the fabric may possess. Along with the flexing of the wire when worn, problems can arise at production. The reed which is fixed to the loom and is used for knocking the weft yarn into position can cause the wire in the weft to snap due to the force used when knocking the weft into place.

The results also highlight that the fusion between rigid and flexible, soft and hard is very difficult to successfully overcome and the integration of wires can be very problematic. These problems can arise at the point of spinning and also when weaving.

Flexibility is an issue. The wire is obviously not as flexible as the yarn and can easily twist back on itself when used in weaving resulting in the wire sitting proud of the fabric.

A decision was taken to approach companies that were able to industrially manufacture spun yarn. If the wires were spun with carrier yarns using the correct machines and processes would this have a bearing on the outcome?

3.4.1 Addressing the findings

Several companies were initially approached to manufacture the yarn but only 2 agreed to spin the yarn. These were Wykes Ltd of Leicester and John L. Brierley Ltd of Huddersfield.

2 methods were investigated for this process. These were air covering and air mingling. Air covering: a jet of air blowing on several yarns and covering one yarn with the remaining yarns. Air mingling: a jet of air blowing all of the yarns together to form one yarn.

Wykes used the air covering process and covered the 0.05mm tinned copper wire with nylon and elastane and Brierley's spun 0.05mm tinned copper wire with cotton and also 0.10mm stainless steel wire with cotton. Both companies had problems with running the wire through the machinery and this resulted in limited supplies of yarn.

The yarn supplied by Brierley's was very good whereas the yarn that Wykes manufactured was not suitable for use. This was due to the wire being insufficiently covered.

Other conductive yarns were sought. Further explorations into the availability of conductive yarns were essential. This led to looking at end uses of conductive yarns with a view of taking them out of context and using them for alternative applications.

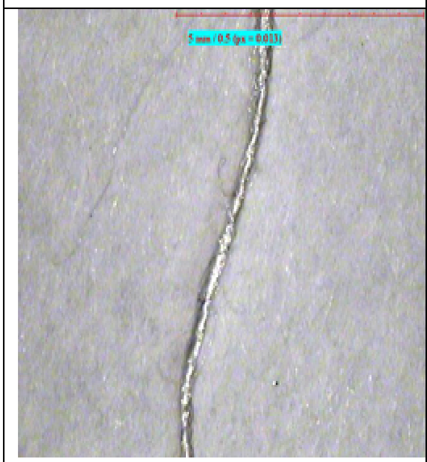
A large amount of conductive yarns are used for anti-static purposes. One particular yarn was BekitexBK50. This yarn is a spun polymer yarn with tiny metal filaments along the length. It retains the characteristics of a normal yarn when woven. This anti-static yarn is used in the backing of carpets.

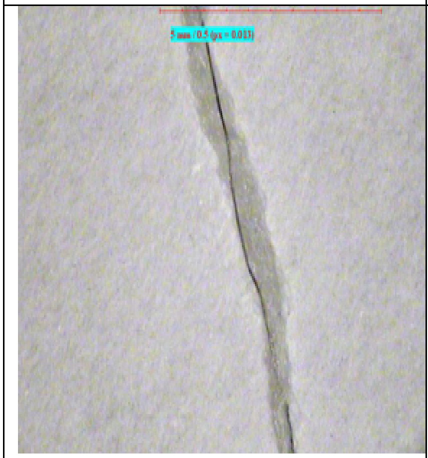
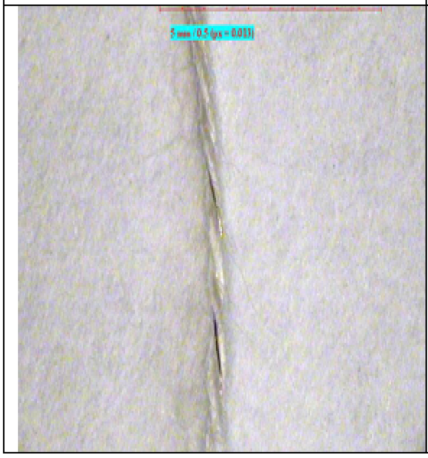
Another anti-static yarn which has already been used in the production of textiles is X-Static.

X-Static is known as The Silver Fibre. During the manufacturing process a layer of pure silver is permanently bonded to the surface of the textile fibre. With this particular process, the yarn, with its silver layer, retains all of the characteristics that a traditional yarn would possess. Quantities of both of these yarns were obtained and further samples were carried out.

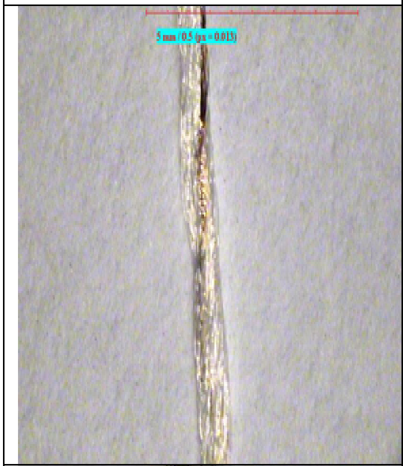
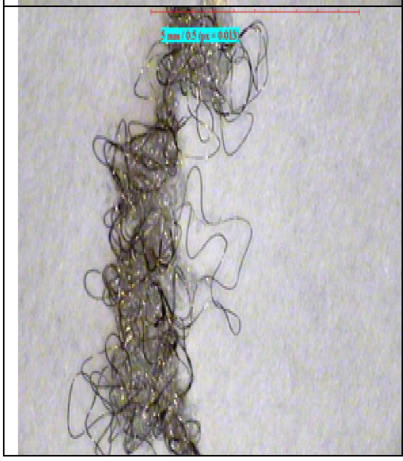
3.4.2 Further conductive fabric samples

Further woven samples were produced to assess the suitability of a conductive cloth.
For these samples the 3 previously used warp yarns were replaced and only one warp yarn was used. This was the Bekitex BK50. This would give an increased conductive surface area as there was a conductive yarn in both the warp and the weft.
The sizes of the samples produced for testing were approximately 6inches x 3inches.
The samples containing the yarns with the integrated spun wires shared many of the characteristics that were found in the initial samples that had already been produced. The following tables show information of the yarns used.

Yarn image	Yarn Used	Supplier	Conductive properties of yarn and length of yarn tested	Characteristics of yarn Once woven
	Bekitex BK50	Kenneth Eames Sillaford Ltd Brighouse West Yorkshire HD6 1DA	850 Ohms Length of yarn tested 18cm	The yarn handled very well with no flexibility issues and the cloth handled like a conventional shirting fabric. Issues arose with the weaving. The yarn pilled and frayed during the weaving process resulting in fragility of yarns. In turn this led to yarns breaking.

Yarn image	Yarn Used	Supplier	Conductive properties of yarn and length of yarn tested	Characteristics of yarn Once woven
	Air covered 0.05mm Tinned copper wire And elastane	Mr Laurie Fluck Wykes Ltd Barkby Road Leicester LE4 9LD	01.2 Ohms Length of yarn tested 20cm	The yarn looked untidy when produced. Once woven the wire was very noticeable in the cloth sample as the surface was very course due to the wires protruding. There was continual snapping of the wire due to the weaving process.
	2/24 cotton spun with 0.05mm tinned copper wire	Marcus Beaumont John L Brierley Ltd Huddersfield HD1 6QT	01.7 Ohms Length of yarn tested 18 cm	The wire was spun with the cotton very well and was hardly noticeable. Once woven the cloth sample felt very good with no issues relating to the flexibility of the cloth.

Yarn image	Yarn Used	Supplier	Conductive properties of yarn and length of yarn tested	Characteristics of yarn Once woven
	2/24 cotton spun with 0.10mm stainless steel wire	Marcus Beaumont John L Brierley Ltd Huddersfield HD1 6QT	00.4 Ohms Length of yarn tested 20cm	With the cotton being quite heavy weight, when spun with the 0.10mm wire it resulted in reasonably heavyweight cloth. There are noticeable flexibility issues when the cloth is folded in the weft direction.
	70 Denier X-Static	Michael J Blake Sigmatex Westhoughto n Bolton BL5 2SL	56.5 Ohms Length of yarn tested 16cm	The cloth sample handles very well retaining natural drape and feel which would be expected from a conventional cloth used for shirting and similar fashion apparel.

Yarn image	Yarn Used	Supplier	Conductive properties of yarn and length of yarn tested	Characteristics of yarn Once woven
	420 polypropylene and 30 denier X-Static	Michael J Blake Sigmatex Westhoughton Bolton BL5 2SL	79.1 Ohms Length of yarn tested 15cm	There is a little stiffness to the cloth sample but the yarn wove very well. The X-Static has given the cloth sample a beige appearance due to its natural colouring.
	30 denier X-Static, air covered with 1/78/46 polyamide and 20 decitex lycra	Michael J Blake Sigmatex Westhoughton Bolton BL5 2SL <u>Air Covering</u> Laurie Fluck Wykes Ltd Barkby Road Leicester	210 Ohms Length of yarn tested 16cm	The air covering worked very well and the yarn wove very well. The cloth sample had good feel to the surface and there was a good amount of stretch also.

3.4.3 Wire sample conclusion

The initial literature search had highlighted the possibility of using wires within the structure of a fabric to give it electrical conductivity. The samples that were produced had not achieved the quality that was originally hoped for.

The results for the electrical conductive properties were taken using a digital volt meter. The readings were taken as an average as there was a fluctuation in the result with using the volt meter probes. A positive connection between probe and yarn may not have been achieved.

The wires that were used were problematic. To overcome a fusion of rigid and flexible and obtain a successful outcome is difficult. The results show that the wires offer a good amount of conductivity but the negative side is that the fabric samples produced, lost the natural feel of a woven fabric. If the antenna was to be produced as a separate piece and then attached to a garment, the wires would be a consideration. As the aim of this project is to produce a totally integrated antenna flexibility issues are a main concern.

The ductility of the wires is a problem. The wire didn't have the capability to sustain large changes in its form. Continual flexing would in turn cause the wire to fracture and at worst break. This would result in the circuit being broken.

Of the yarns tested, the samples woven from the Bekitex BK50 and the X-Static were the most successful in retaining a natural drape and feel. However, as the results table shows, the electrical conductivity of the Bekitex was poor. It was better in the X-Static but still not as good as it was with the wires.

Problems also arose when weaving with the Bekitex. The yarn was prone to pilling and fraying with the reed continually moving forward and back. This could have been rectified by coating the yarn.

In order to ascertain the suitability of the yarns, further tests would need to be carried out and tested using a different piece of equipment.

Small conductor lines were woven in the cloth and they were tested using a microwave scalar network analyser with vector reflection analyser.

3.5 LOW FREQUENCY FABRIC SAMPLES

Low frequency samples were produced in order to further test the conductive yarns. A small conductor track was woven in the weft in the middle of a cloth sample (fig 32). The cotton was woven in the weft either side of the conductor track. The tracks needed to be only 1mm - 1.5mm in thickness and 7mm in width. The number of picks[60] varied due to the differing sizes of the conductive yarn used.

The tracks were produced using a variety of yarns, even if some of those yarns were dismissed in the earlier weaving tests.

The table shows the yarns that were used and the number of picks to reach the 1 – 1.5mm thickness.

YARN USED	NUMBER OF PICKS
Bekitex BK50	5
70 Denier X-Static	10
0.05mm tinned copper wire with 2/24s cotton	3
0.10mm stainless steel wire with 2/24s cotton	3
1 x 420 polypropylene / 1 x 30 X-Static	3
1 x 100 grey polypropylene / 1 x 30 / 1 ccw / 5% X-Static	4
30 Denier X-Static – 10 strands only	18

The loom was threaded using 2/40s cotton at 64 ends per inch and there were a total of144 ends. An 8 shaft table loom was used to carry out the tests.

The metallised track was added as an additional weft yarn. This was inserted after approximately 2.5 inches of cloth had been woven. It was inserted in shafts 1-3 and 5-7 which was the conductor track. An additional 2.5 inches of cloth was then woven afterwards making

[60] Picks refer to the weft yarn that is woven through the warp ends.

the finished sample approx 5-6 inches in length. This was to allow enough fabric to be clamped in the microwave scalar network analyser.

Fig 32 shows the X-Static conductor track and its position in the cloth sample, authors own image

Fig 33 shows a close up of the X-Static conductor track. The red circle highlights the untidy end of the track, authors own image

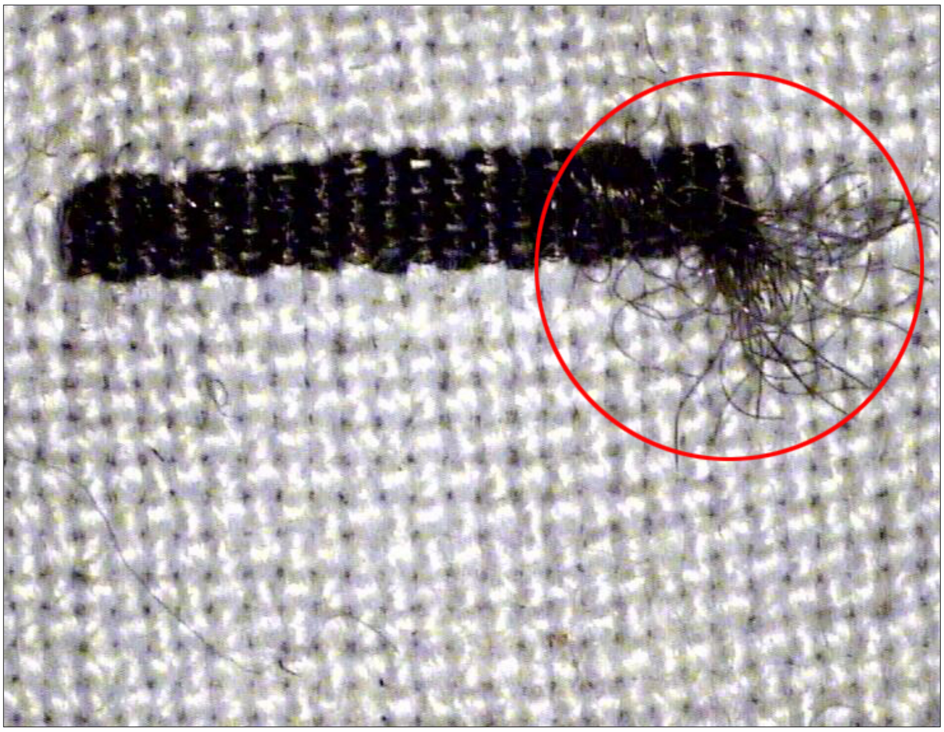


Fig 34 shows the 0.10mm and 2/24s cotton conductor track highlighted by the blue rectangle. The 2 red circles show the holes where the sample is fixed in the analyser, authors own image

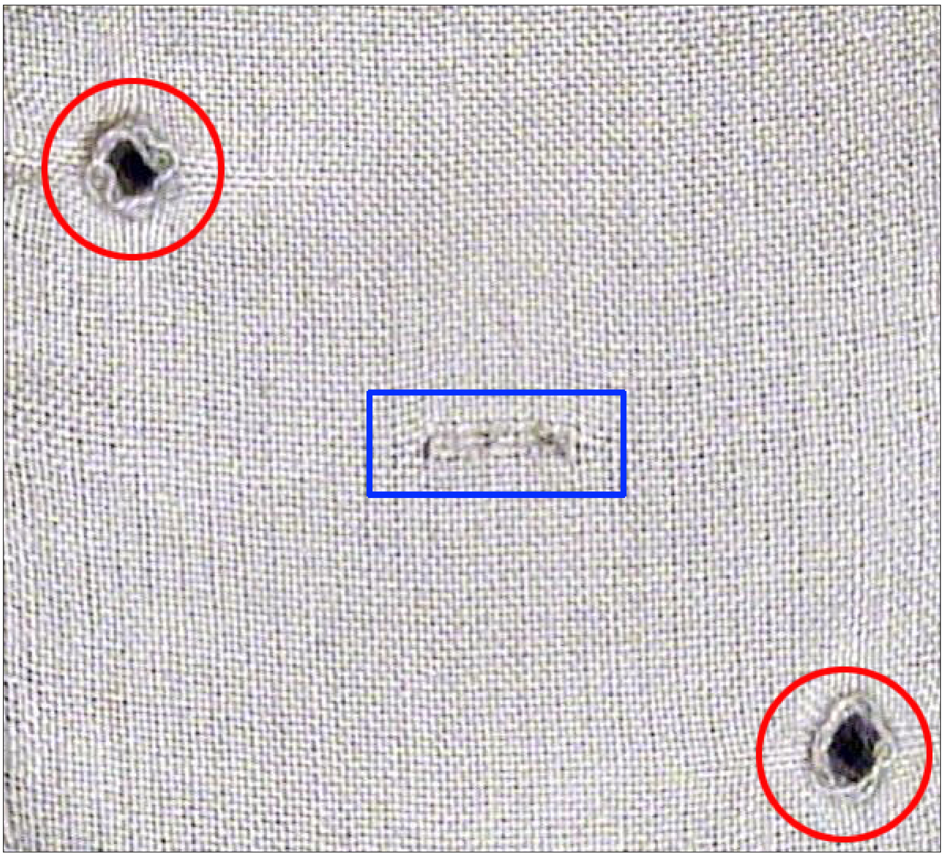
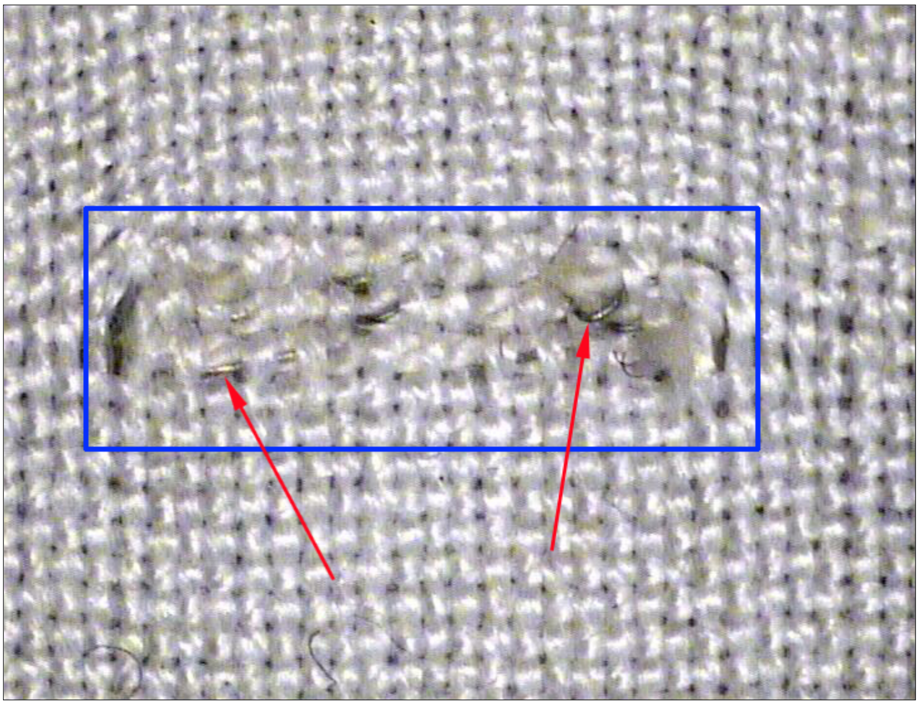
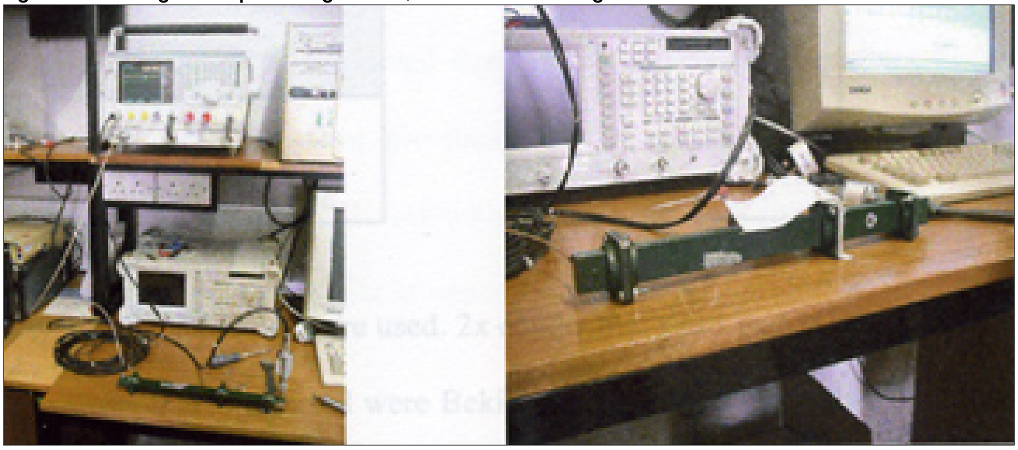


Fig 35 a close up of the conductor track can be seen in the blue rectangle. The red arrows indicate where the wire is sitting proud of the surface of the cloth, authors own image.



The samples were then tested in the Department of Electrical Engineering. The results were ascertained by using a microwave scalar network analyser with vector reflection analyser, this would test the conductivity of the yarns used, Fig 36.

Fig 36 an Image of the low frequency testing using microwave scalar network analyser, the image on the right is showing a sample being tested, authors own image.



This piece of equipment was used as it measures the amount of power being passed through the conductive line to ascertain whether it is a good carrier/conductor of power or not. It is difficult to say if the results obtained were conclusive. The connection between the wave guide analyser and the fabric sample may have been unreliable.

The results of these tests can be seen in the appendix.

1 yarn which gave an indication that it could be useful was the 0.05mm tinned copper wire. However, during previous tests the fragility of the 0.05mm Tinned copper wire was evident and unsuitable for use. The 70 denier X-Static, although not having the same amount of conductivity as the wire, did show signs which were encouraging.

At this point further conductive yarns were to be sourced.

Enquiries were made to source alternative conductive yarns but this proved to be more difficult than originally anticipated.

Several companies were approached with a view of obtaining samples of conductive yarns in order to complete further woven tests.

The companies approached were

Shanghai Xinlun textile & Auxilaries VCo.

Marktek-inc

Dupont advanced fibre systems

Shakespeare Conductive fibres

Swisstulle UK P.L.C

Bekaert

Aramid.

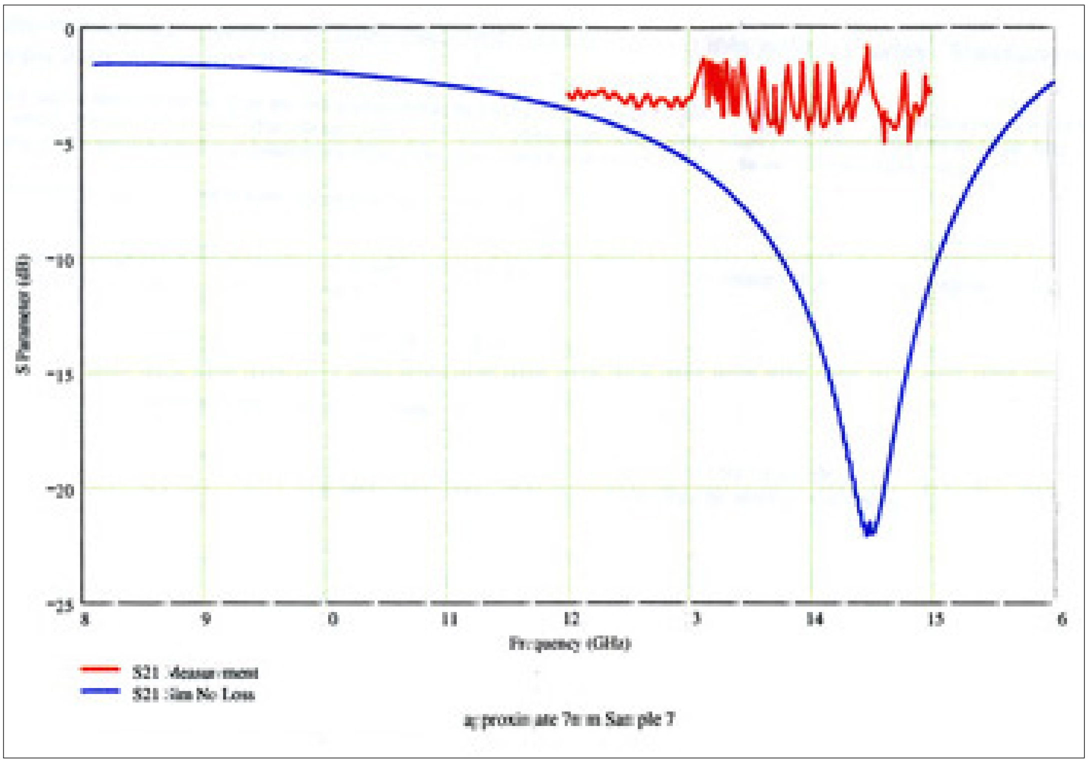
There was little success in obtaining any alternative yarns from these suppliers.

4 of the named companies never responded to the emails. The remaining companies replied with only one promising to send a yarn. No samples were received.

Whilst waiting on the other yarns, a re-examination of the test results carried out on the waveguide analyser were undertaken.

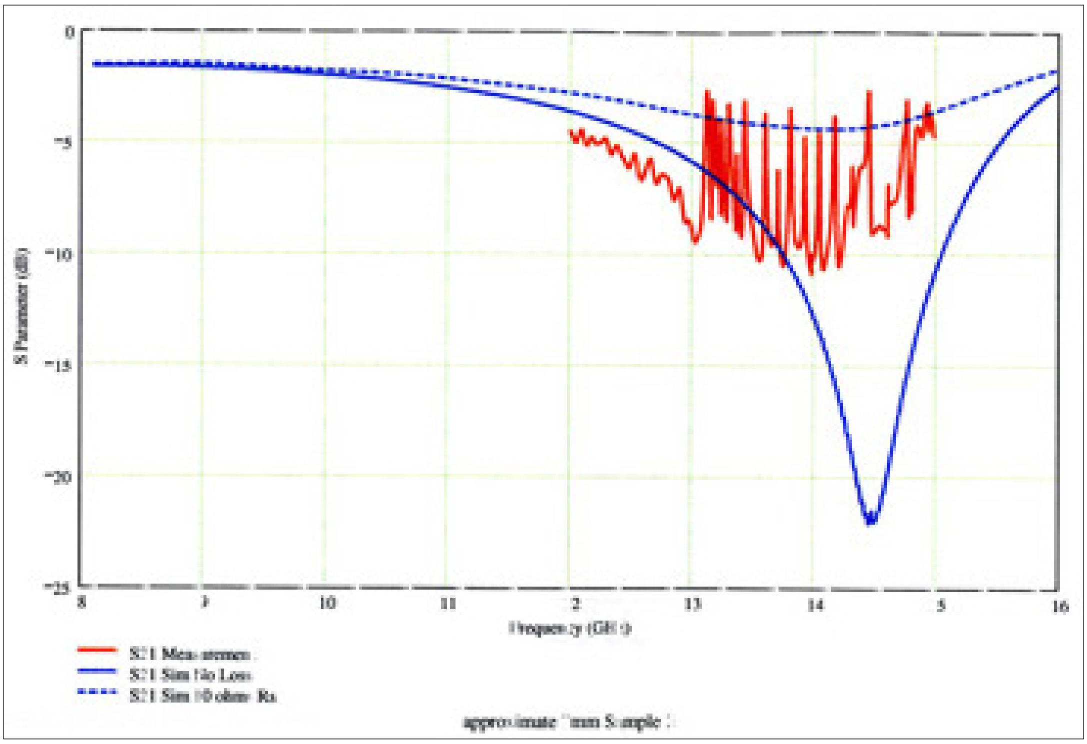
Once the results were analysed for a second time, it became apparent that the results were far more informative than was first thought. It wasn't clear at that time but the difference in results between the 30 denier (fig 37) and 70 denier X-Static (fig 38) proved to be the catalyst in moving the investigation forward.

Fig 37 printout of the 30 denier X-Static metallised track result



The previous image shows the test result of the 30 denier X-static. The blue line is the simulated curve and the red line being the sample 30 denier X-Static. It was hoped that the results would show the red line, to some extent, follow the curvature of the blue line.

Fig 38 Printout of the 70 denier X-Static metallised track result



Although showing a lot of noise (erratic line as opposed to a smooth line), the above result of the 70 denier X-Static shows there is more movement than that seen in the 30 deiner. Curvature of the line is evident whereas there was none being shown in the 30 denier sample. The noise being shown on the line is due to the waveguide analyser not being able to test such a high frequency. The noise doesn't hinder the result. The information gained from this, albeit limited, showed that the increase in denier gave a slightly better result. This raised the question, 'would an even bigger increase in denier prove to be more successful?'

With this is mind, the 30 and 70 denier yarns were spun together to create varying deniers of yarn. These would then be used to produce further samples. A sample of 200 denier X-Static was obtained from the UK X-static representative. This was also used for further tests on its own rather than being spun with the 30 and 70 denier.

The 70 and 30 denier X-Static yarns were spun together to create the following multiply yarns;

100 denier – constructed using 1x70 denier and 1x30 denier

140 denier – constructed using 2x70 denier

170 denier – constructed using 2x70 denier and 1x30 denier

210 denier – constructed using 3x70 denier

280 denier – constructed using 4x70 denier

350 denier – constructed using 5x70 denier spun with silk.

The yarns were again spun together using the method which was used previously, with a cordless drill. The unorthodox method was acceptable for the smaller samples but for a larger set of samples the yarn would need to be obtained in the correct denier.

The new yarns were then again woven into a conductor track and to the same specifications as before, 7mm in width and 1- 1.5mm in thickness.

The sizes were achieved in various amounts of picks depending on the denier used. The pick count was as follows;

100 denier – 10 picks

140 denier – 7 picks

170 denier – 5 picks

210 denier – 4 picks

280 denier – 4 picks

350 denier – 3 picks

200 denier – 4 picks

3.5.1 Analysis of new metalised track results

The new X-Static samples underwent the same tests as the previous sets. Not all measurements were encouraging but it was hoped that a clearer indication of a suitable yarn could be ascertained after these tests.

The results did however support the theory that an increase in denier would in-turn give an increase in performance from the yarns used.

The yarns that were not performing so positively were the 100 denier, 170 denier and 280 denier. The remaining yarns were showing signs that the measurements were beginning to follow the line of the simulated 7mm conductor track.

Although the measurement results show a significant improvement, further tests were required to establish a suitable yarn or yarns to use to construct an antenna.

3.6 CONTINUAL CONDUCTOR LOOP SAMPLES

The conductor tracks were 7mm in width. For a more comprehensive set of results and a further defined indication of a suitable yarn, a 26mm conductor track was required to be measured. As the width of the waveguide analyser could only measure a little over 7mm, the 26mm conductor track would need to be constructed in a continual conductor loop in order to fit within the waveguide parameters. The loop would be constructed with 7mm of yarn in the height and 6mm in width. This would give 2 x lengths of 7mm and 2 x widths of 6mm giving a total of 26mm. The width was to be the same as used in the previous conductor track, 1mm – 1.5mm. This size would also need to be achieved in the additional warp ends.

The track was constructed in an almost square shape in order to fit within the waveguide analyser. With this increase in size particular care needed to be taken when clamping the sample between the analyser. If not, there was a chance that a false measurement would be recorded if any of the conductive yarn was sitting outside of the measurable area.

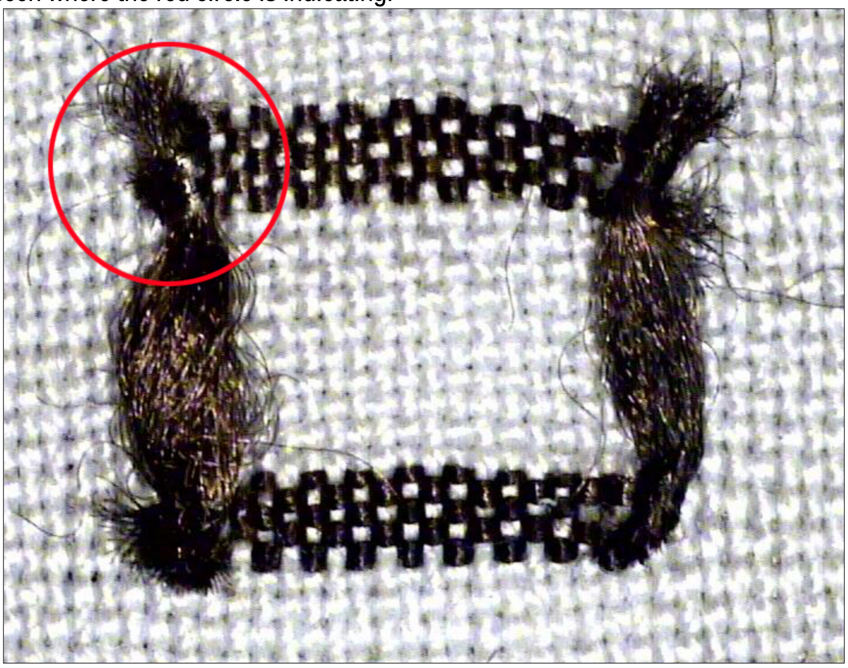
The construction of the conductor loop was slightly cruder than expected due to time restraints and the small amount of samples needed. In order to weave the continual loop samples using the correct method, an additional floating warp would be required but this would be very difficult and time consuming. A decision was taken to lay the additional warp on top of the original warp and tie it in at the corners using the structure of the plain weave to secure it. The number of ends either side varied depending on the denier used. The table shows the denier used and the amount of ends used

Denier of yarn used	Ends either side
200 denier	4
210 denier	3
350 denier	2
170 denier	4
280 denier	2
140 denier	4
100 denier	4

The samples on the whole were a little untidy and gave slight cause for concern as some of them needed to be stitched together on the corner joints. This can be seen in fig 39 It was unknown if these corrections would interfere with the measurements but it had to be considered that any results taken may not be totally true. If a successful results outcome was obtained and further samples were required then the warp would have be integrated in the correct manner.

Fig 39 Image of X-Static continual conductor loop sample, Authors own photograph

Fig 40 close up of the 26mm conductor loop. The untidy finishing on the warp and weft joins is evident and can be seen where the red circle is indicating.



Although there were yarns that performed better than others during the previous set of tests with the 7mm conductor track, it was decided that all of the yarns would be tested again.

The same measuring method was used and the same frequency range was used, 8-15 GHz. The tests showed differing results to those of the previous tests. It was also interesting to note that the samples that looked promising before were not performing so well during these tests. There was a possibility that the yarns were not sitting correctly within the waveguide analyser therefore a false measurement could have been recorded. The samples were re-tested after they were re-positioned in the analyser and a better measurement was obtained. The corrections that were made to the samples in terms of the stitching appeared to have been successful as the sample measurements were unaffected by this.

3.6.1 Analysis of conductor loop test results.

The majority of the samples proved to be successful when tested apart from the 200 denier X-Static. This was one of the better samples when measured in previous tests which raised questions as to why they perform differently when measured in the same way. A differing test result may have been obtained due to the sample not sitting correctly within the waveguide analyser.

Of the 7 samples that were tested, the 2 yarns which indicated a suitable use were the 350 denier X-Static and the 170 denier X-Static. These were the most significant results that had been recorded to date and the possibility of producing 2 antennas in differing weights was evident.

The size and shape of the antenna was still to be decided at this point but the possibility of a lower frequency antenna, approx 2.5GHz, had not been ruled out. This may well give a better result but it would increase the size of the antenna. A higher frequency would result in a smaller antenna but the process of weaving it would then become a little more difficult as the antenna becomes increasingly intricate.

3.6.2 CONCLUSION OF METALISED TRACK TEST RESULTS

Each set of test results had informed the following stage of the investigations. The last set of test results gave very promising outcomes, to the point where 2 yarns had been identified for use in the construction of a textile antenna.

If the results had proved to be negative in all of the tests that were carried out then the research investigations would suffer immensely. Positive results were paramount in order for the aims and objectives to be met.

At this point investigations were behind schedule. It had been hoped that an antenna design would already have been sampled. Finding a suitable conductive yarn had proved more difficult than anticipated.

After the testing of the conductor loops it was apparent that producing a range of fabrics may have been unrealistic. This was due to the time taken in testing everything and with the enormity of the project, it was hoped that 2 prototypes could have been realised. One light weight sample, the other heavy weight.

With having identified 2 yarns to proceed with, the next stage of the investigation was for the department of Electrical Engineering to design an antenna to be sampled on the loom.

The department of Electrical Engineering supplied illustrations, with specific dimensions, of 3 different antennas. These were a Dipole antenna[61], a folded Dipole antenna[62] and finally a patch antenna[63]. The practical investigations were to incorporate these antenna designs into woven cloth samples.

Alongside this, work was taking place on the second part of one of the research questions. Along with textile antennas, textile transmission lines were to be investigated. These are an important component of textile antenna construction as they are used to transfer power to the antenna itself.

This work was carried out by Thomas Hill and the investigations and results can be found in chapter 4.

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[61] an aerial consisting of two parts connected to a transmission line at the centre

[62] The same as a dipole antenna but with an additional section connecting the ends this generates 2 radiating currents

[63] A flat panel antenna, rectangular or square

3.7 DESIGN AND CONSTRUCTION OF A TEXTILE ANTENNA

All antennas produced were woven using 170, 280 and 350 denier X-Static. The woven structure used to facilitate the antennas was the plain weave. As previous tests showed, this was the strongest and easiest structure to use due to the simple over and under direction of the yarn. This would also give a larger concentrated area of conductivity due to the conductive yarns being in close proximity to one another.

The X-Static yarn was introduced as a separate weft using an additional shuttle to weave the yarn alongside the cotton yarn. This process was used across all of the antenna designs.
3 different antennas designs were worked on. These were a folded dipole antenna, a dipole antenna and a patch antenna. These are standard antennas used in mobile communications.

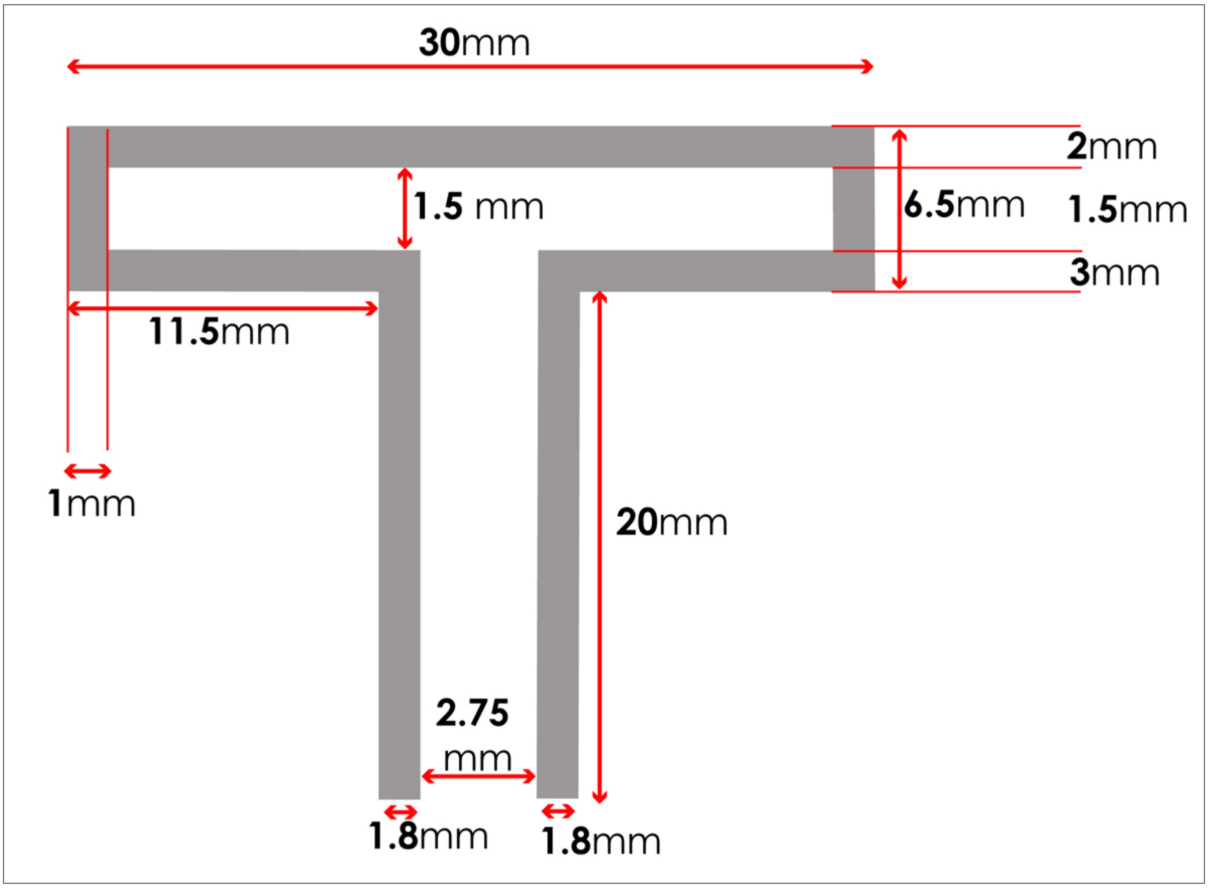
The initial antenna sample tests were carried out on a hand and foot operated wooden Dobby Loom. If a successful and reliable antenna was sampled on the Dobby, the antenna would then need to be sampled on a modern manufacturing loom. For these investigations it is hoped that the antenna can be produced successfully on both the hand operated and electrically controlled looms. However there are potential problems. The power of the mechanical loom might stress the yarn and potentially snap it, resulting in a broken circuit. On the plus side, the antenna may be woven closer and more compact giving a more concentrated area of conductivity resulting in a more successful radiating performance.

3.7.1 FOLDED DIPOLE ANTENNA

The antenna would be introduced into the cloth at the point of production. The cloth was woven using a 2/30s cotton with 48 ends per inch and to a width of 3.25 inches. It was not necessary to weave the cloth any wider due to the size of the antenna being only 3cm in width.

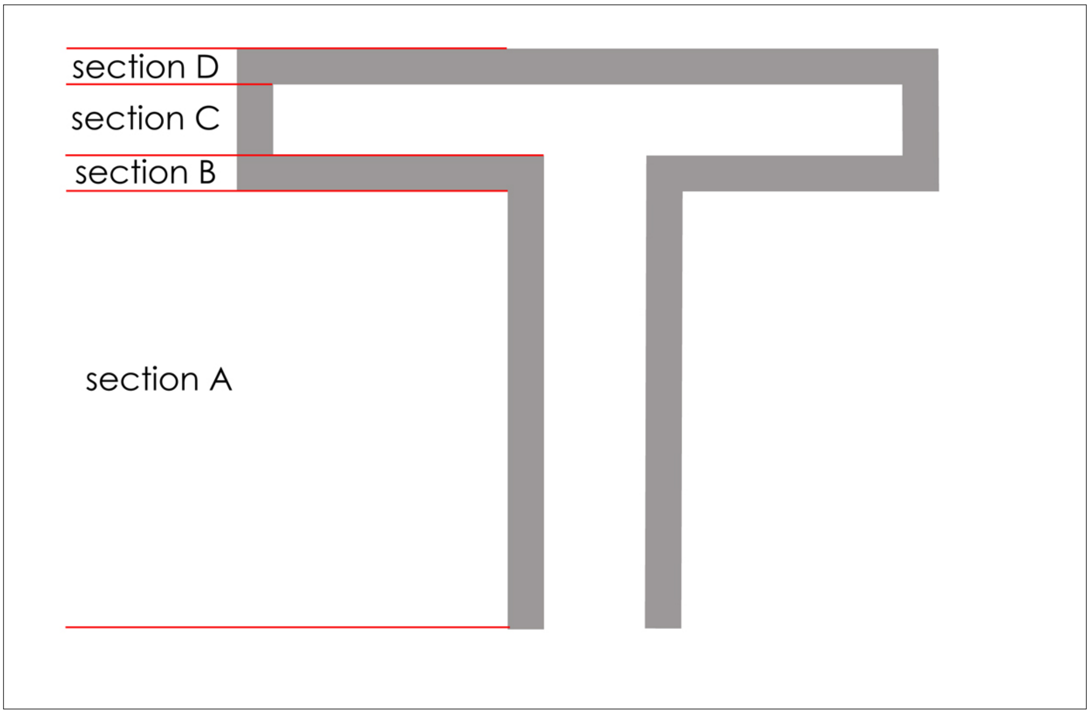
The image shows the antenna design with the measurements of the required parts.

Fig 41 Illustration of the folded dipole antenna with measurements from the Dept of Electrical



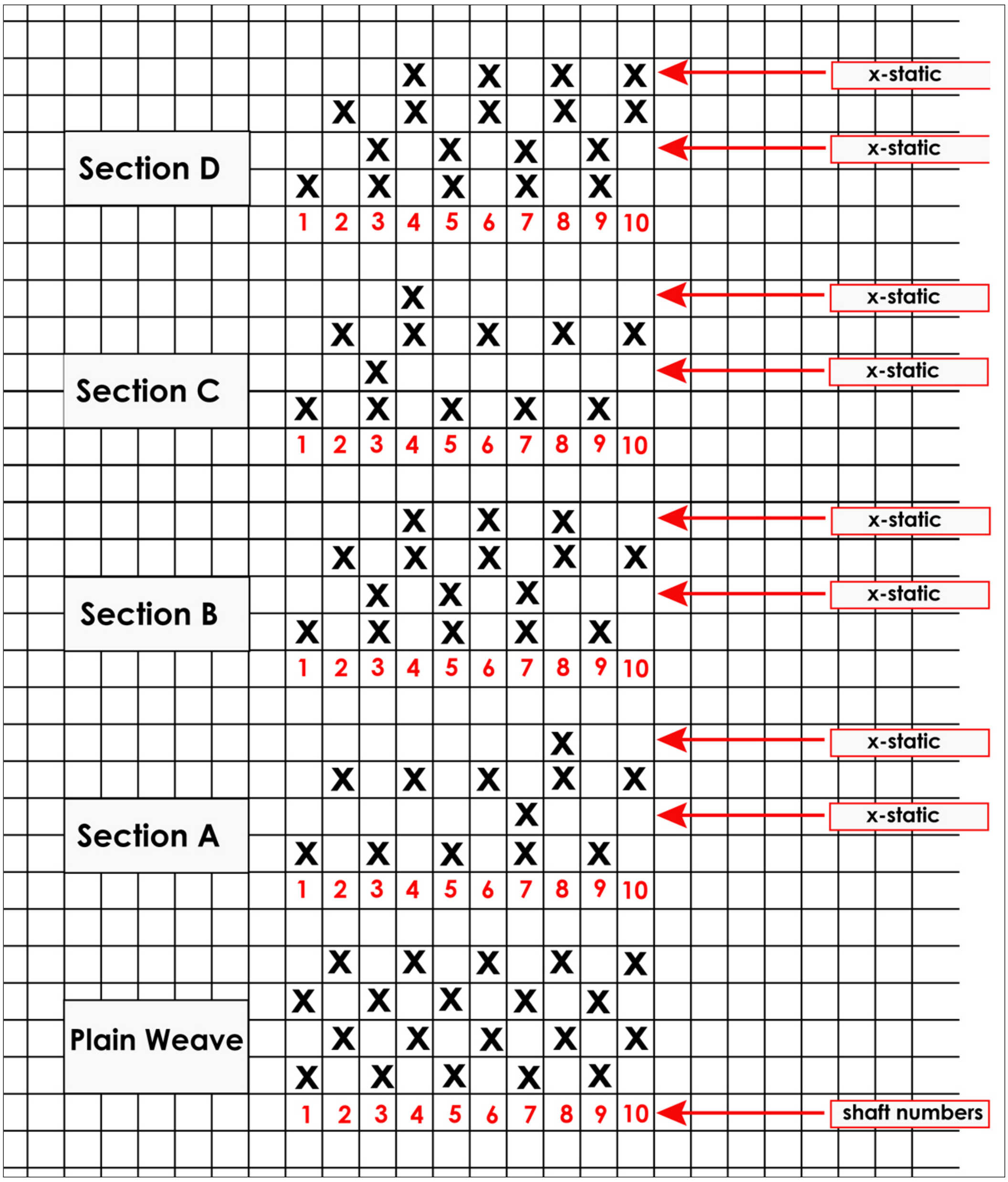
The design was broken down into sections A, B, C and D in order to work out the weaving lifting plan.

Fig 42 image showing the antenna design divided into sections



The lifting plan (fig 43) is shown overleaf with the red arrows indicating where the X-Static was introduced in the relevant section.

Fig 43 shows the lifting plan for the folded and dipole antennas. The relevant sections are clearly identified as is the introduction of the X-Static yarn



The design of the antenna is a challenging one. The antenna was woven with the introduction of 2 additional X-Static yarns in the weft. Precision and a reliable method in reproducing the antenna were paramount.

As can be seen from the following images (Fig 44 - 47) a precise and reliable reproduction was not achieved.

Fig 44 Image of a woven folded dipole antenna using 170 denier X-Static, Authors own photograph

Fig 45 Image of a woven folded dipole antenna using 350 denier X-Static yarn, Authors own photograph

Fig 46 Close up image of Woven folded dipole antenna illustrating the raised nature of the yarn. Authors own photograph

Fig 47 Close up image of woven folded dipole antenna illustrating again the raised nature of the X-Static yarn, Authors own photograph

The images illustrate the problems that weaving a folded dipole antenna caused.

The images clearly show the raised nature of the woven X-Static yarn on the 2 vertical planes. The horizontal planes also display poor structure. The curved nature of the woven piece may have significant bearing on the performance as the woven antenna doesn't have the dimensions required. There is a good chance that the raised surface of the structure was due to the X-Static being used on consecutive picks. If it was used on every other pick with the cotton being placed in-between, this may resolve such problems.

Fig 48 shows within the red lines the untidy finishing of the antenna; the loose fibres could be problematic with the possibility of them of them being pulled.

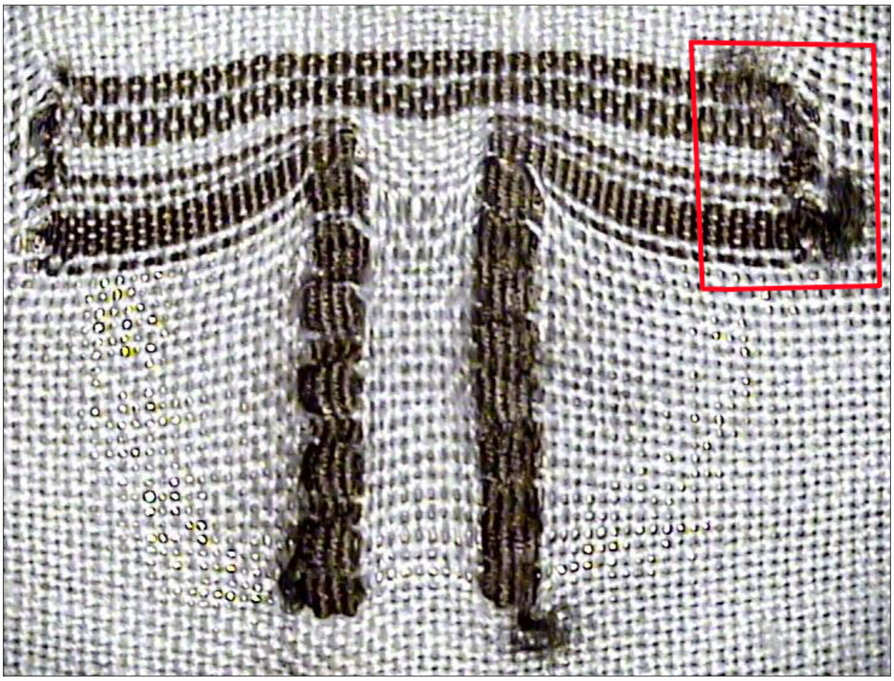
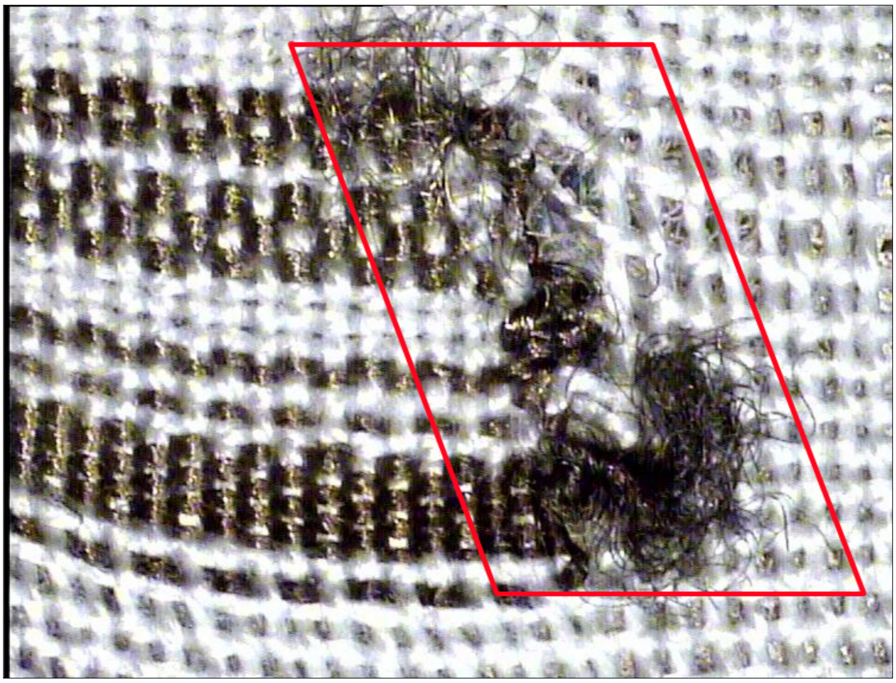


Fig 49 shows a close up of the problem area with the loose fibres



Overall the antenna has a very poor appearance and totally unusable due to the raised yarns being so prominent that catching, pulling and scuffing would be a regular hazard. The fabric is also puckered around the antenna. The finishing, in terms of the end of the antenna is also a concern. There is not a clear end when the antenna was woven and on the samples it is clearly visible that there is an untidy frayed end. This not only looks unfinished but also problematic as there as loose fibres which could catch and pull but also could give rise to unreliable test measurement readings.

The aim was to integrate an antenna where the fabric retained all of its original qualities of feel and drape. These initial samples show that there was a lot of work to do.

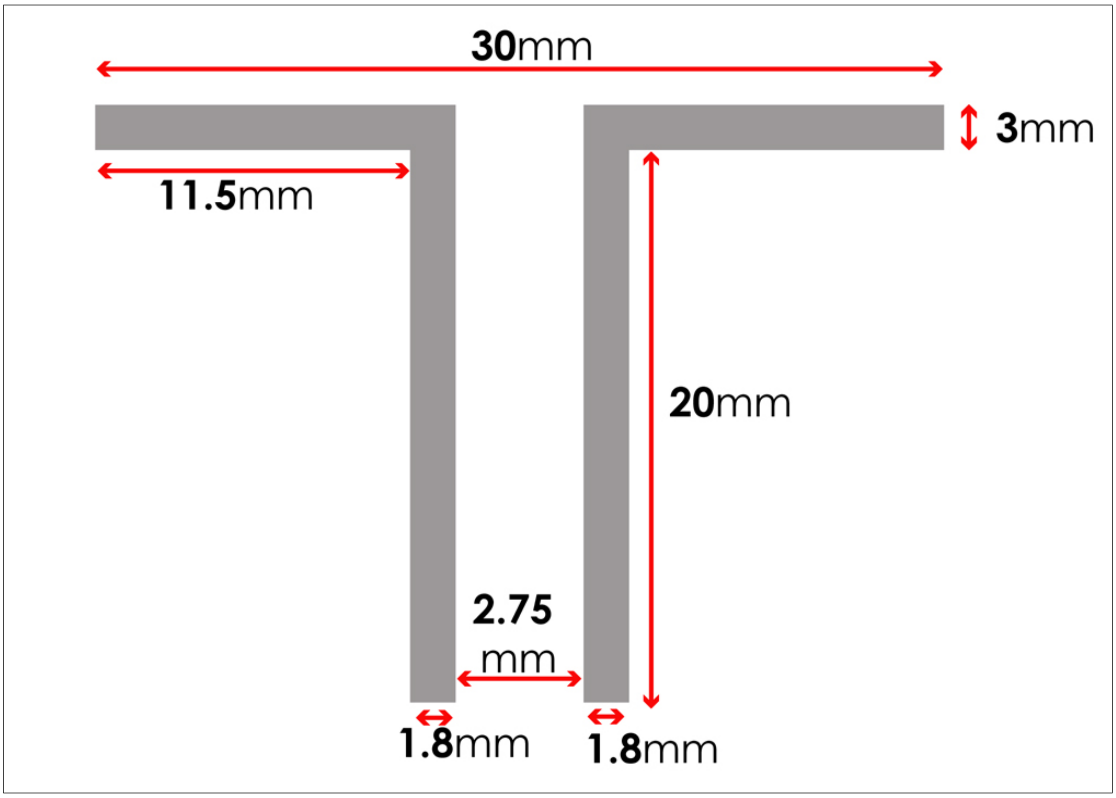
The construction of this type of antenna wasn't wasted. It highlighted the fact that this type of antenna wasn't going to be produced easily and reliably. Even though the antenna looked poorly constructed, it was tested using the wave guide analyser in order to see what actual performance was given.

The fabric antenna was tested alongside a conventional copper folded dipole antenna that was used in mobile communications. The results are examined in chapter ……..

3.7.2 DIPOLE ANTENNA

The Dipole antenna is very similar to the folded dipole, the difference being that the Dipole only has the bottom section of the horizontal plane as opposed to the complete top section of the folded.

Fig 50 Illustration of the dipole antenna with measurements to be woven, not to scale



With the problems that were encountered with the weaving of the previous folded dipole, puckering and raised surfaces of the yarn, the dipole antenna was woven using alternate picks. It was hoped that the antenna would sit better on the surface of the cloth. The X-Static was again introduced separately as 2 additional yarns in the weft.

The image overleaf shows the antenna divided into sections. This was done to make the weaving drafting plan easier. The loom was set up exactly the same as it was for the folded dipole antenna.

Fig 51 the illustration shows the antenna divided into sections A and B

The table shows the 3 deniers that were used and the number of picks used in each section. The actual sizes required and the final realised sizes are also shown.

Denier	Picks in section A	Picks in section B	Required Height & Width of section A	Realised sizes of Section A	Required Height & Width of section B	Realised Sizes of section B	Required Space between Vertical lines	Realised Space between vertical lines
280	39	5	H-20mm W-1.8mm	H-19mm W-2mm	H-3mm W-30mm	H-3mm W-29.5mm	2.75mm	4.5mm
350	39	5	H-20mm W-1.8mm	H-20.5mm W-2mm	H-3mm W-30mm	H-3mm W-30mm	2.75mm	4.5mm
170	36	6	H-20mm W-1.8mm	H-19.5mm W-2mm	H-3mm W-30mm	H-3.5mm W-29mm	2.75mm	5mm

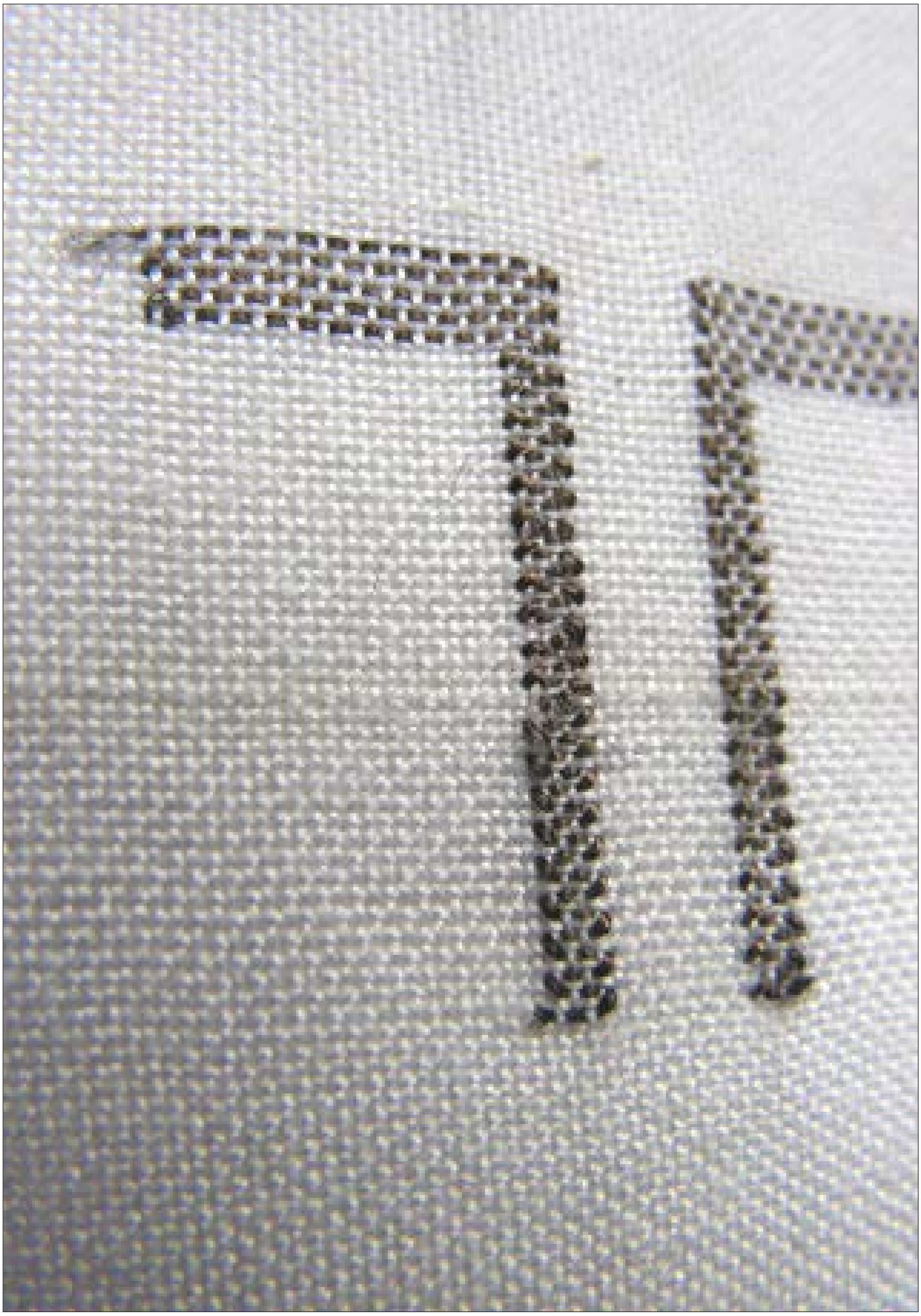
The images show the woven dipole antennas (Fig 52-55). It is evident that the initial appearance is encouraging. The antenna is sitting a lot flatter on the surface of the cloth. Closer inspection does indicate imperfections in the weaving and the vertical elements of the antenna highlight irregularities.

Fig 52 Image of a woven dipole antenna using 280 denier X-Static yarn. Authors own photograph

Fig 53 Image of a woven dipole antenna using 350 denier X-Static yarn. Authors own photograph

Fig 54 Image of a woven dipole antenna using 170 denier X-Static yarn. Authors own photograph

Fig 55 Image of a woven dipole antenna, Authors own Photograph



The irregularities are more noticeable on the 350 denier (Fig 53) and 170 denier samples (fig 54). The 280 denier (Fig 52) appears to be the most successful in terms of aesthetic appearance. There is still a problem with the finishing of the antenna. The images illustrate that there are still loose ends showing. This could be trimmed closer to the cloth but there is still the possibility that it may work loose from under the warp thread.

Aesthetically, the samples produced were not acceptable as they too look untidy.

3.7.3 FOLDED DIPOLE AND DIPOLE TEST PROCEDURE

The tests on both the Dipole and the Folded Dipole were carried out using a Balun (balance/unbalance) which was connected to a wave guide analyser. The purpose of the Balun is to drive the electrical current outwards, and equally to both sections of the antenna. The images (Fig 56 and 57) illustrate the test procedures and the manner in which the antennas were connected to the test equipment.

The fabric antenna was tested along with a standard copper folded dipole antenna which would be the comparison to work to. Both the copper and fabric antenna were tested using the same method.

The images highlight a potential problem with collecting reliable tests results. The 2 copper prongs on the Balun sit on the antenna when testing is undertaken. With the copper antenna the prongs are touching a rigid substrate. When the same tests are carried out on the fabric antenna, the connection between the copper prongs and the textile antenna may not have such a strong and reliable connection. With this in mind, it may have a bearing on the test results with them not being as accurate as they could be.

The results are gathered and shown to easily compare the measurements between the copper and the textile antenna.

Fig 56 Image showing a conventional copper folded dipole antenna connected to the Balun. The red oval indicates the join between the copper prongs and the copper antenna. With them both being of a rigid substrate a firmer connection can be attained. Authors own photograph

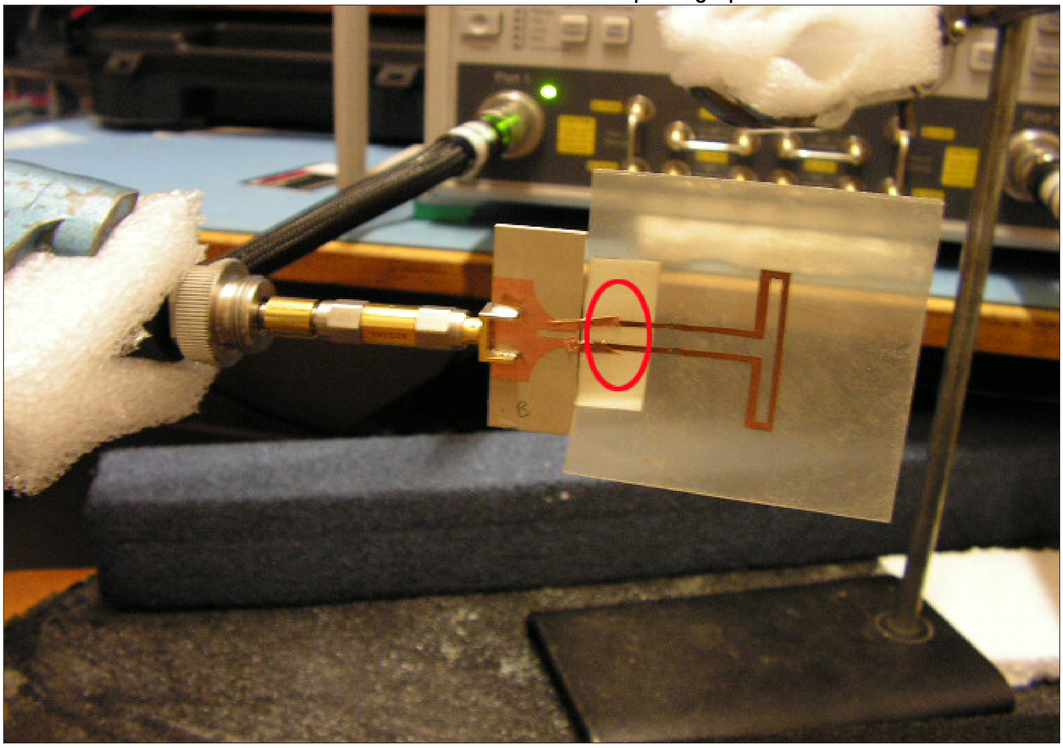
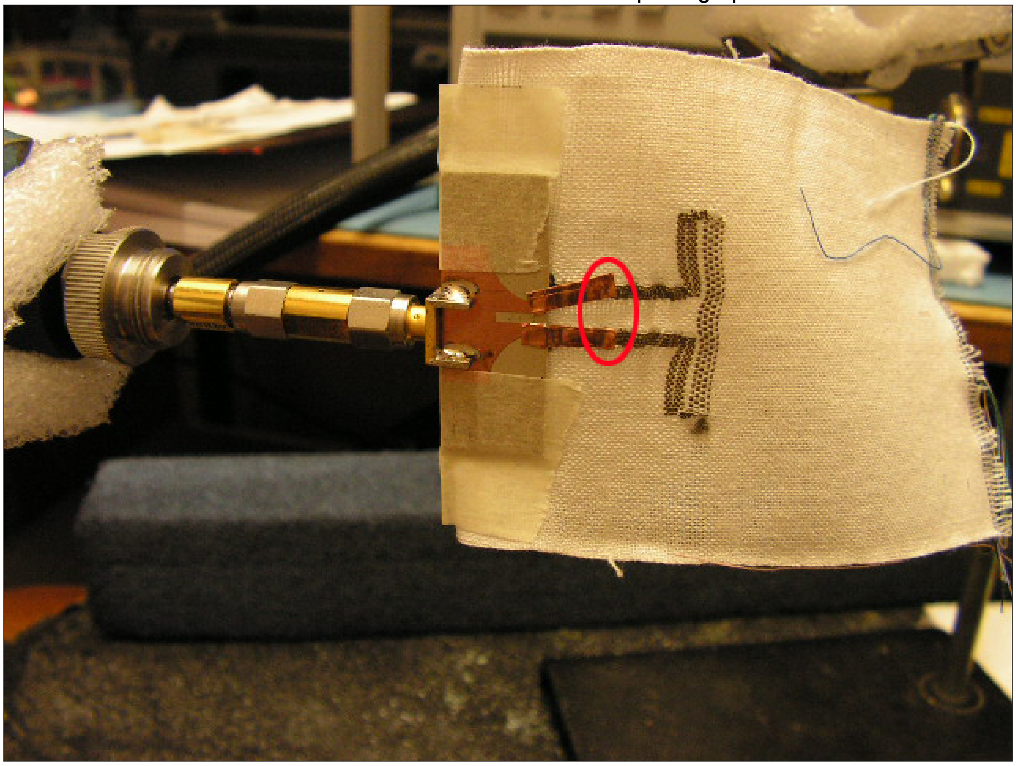


Fig 57 Image shows the woven folded dipole antenna connected to the Balun. The red oval again indicates the join between the copper prongs but this time the fabric antenna. This rigid to soft substrate connection could cause unreliable test results. Authors own photograph



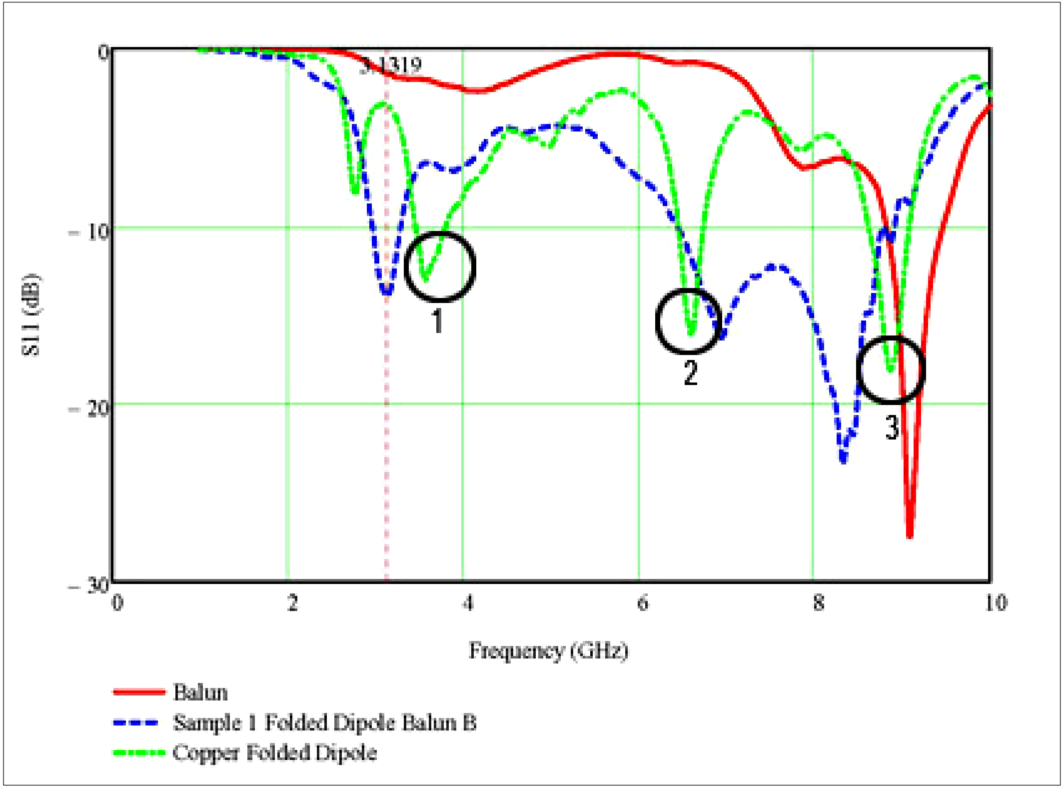
3.7.4 FOLDED DIPOLE TEST RESULTS

The test results will try to indicate whether the initial antenna samples show encouraging signs and that they may be suitable for further investigation.

A simplified explanation of the test results follows which will allow a textile/design based audience understand what the results are showing.

Figure 58 shows the first fabric Folded Dipole sample measurement, along with that of the copper antenna. The antenna tested was constructed of 170 denier X-Static with it being used every alternate pick.

Fig 58 printout of test result of a fabric folded dipole and copper folded dipole.



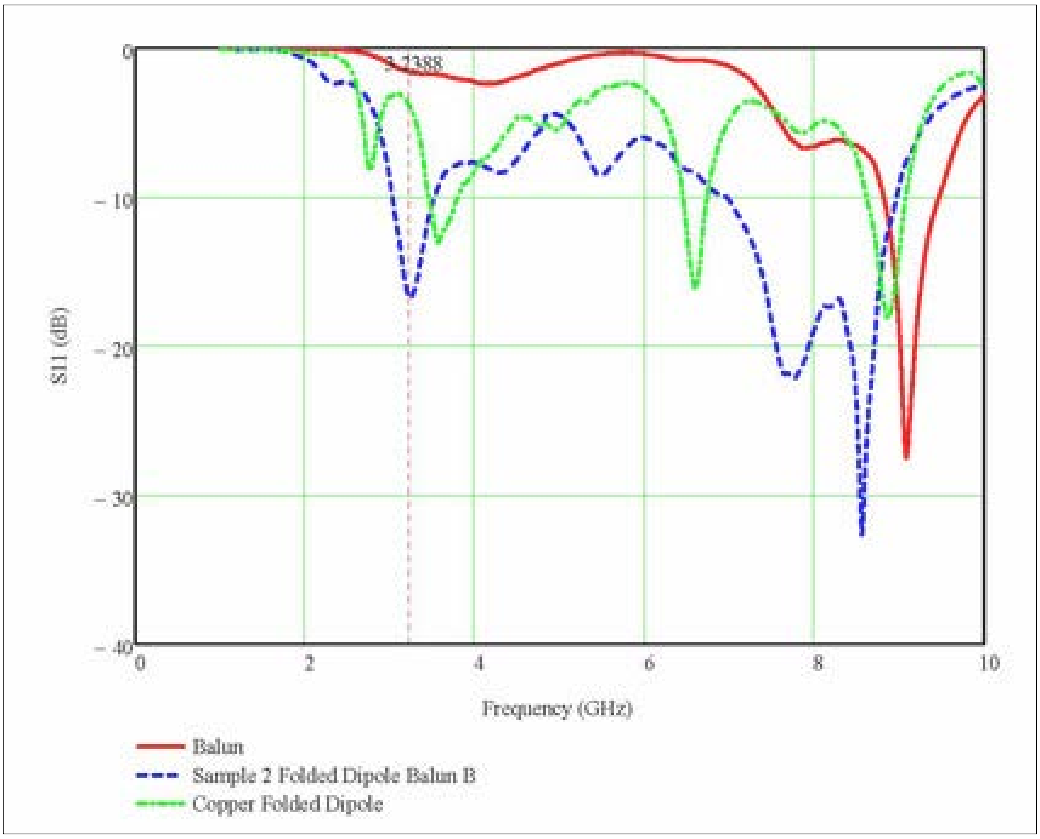
The 3 visible lines show the balun (red), the fabric antenna (blue dashed line) and the copper folded dipole (green dashed line). Ideally the results would have the blue dashed line replicating, to some extent, what the green line is doing.

The copper (green) measurement shows that there are 3 main troughs, indicated with the numbered black circles 1, 2 and 3. The vertical green lines are relatively close together. The fabric measurement, shown with the blue dashed lines, shows a similar pattern with 3 troughs. The blue vertical lines are spaced wider apart. This indicates that the antenna is lossy. Some of the electrical current going into the antenna is being lost. This could be a result of the yarn used not being as reliable as it could be or the construction of the antenna not being satisfactory.

In simple terms this means that the antenna is not as efficient as it could be.

With this information in mind, the remaining folded dipole results are shown below which show if any of the antennas would be suitable for further investigation.

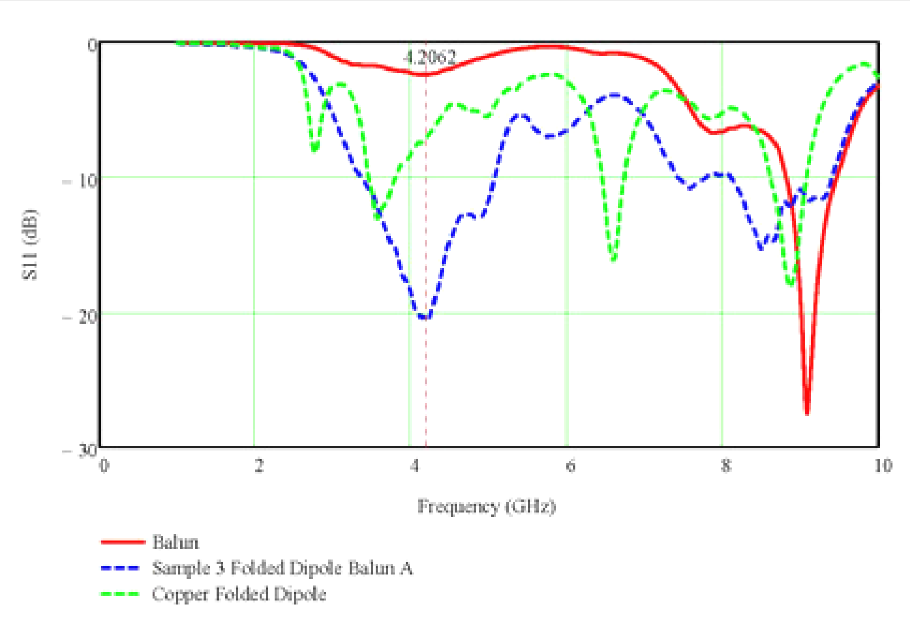
Fig 59 printout of test result of a fabric folded dipole and copper folded dipole.



The image above shows the results of the 350 denier folded dipole antenna with the X-Static being woven in alternate picks. Again there are some encouraging signs although it is still lossy.

Figure 60 overleaf shows the result of the 170 denier X-Static, but with virtually every pick being the X-Static as opposed to the previous result which showed alternate picks.

Fig 60 printout of test result of a fabric folded dipole and copper folded dipole.

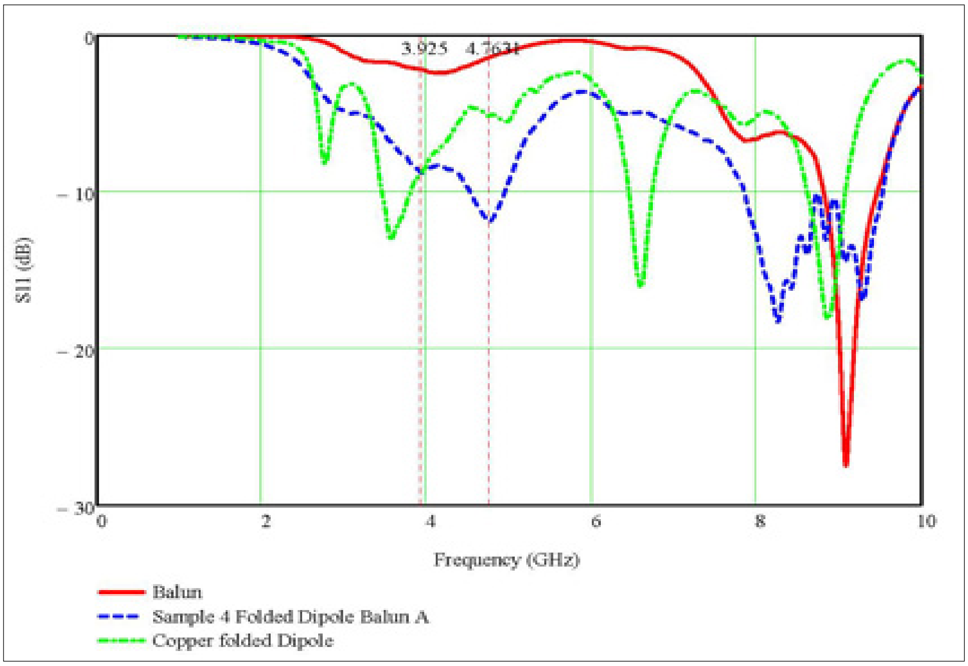


The blue dashed line of the textile antenna shows the peaks and troughs to be shallow and spread apart, indicating a lossy antenna. It is evident from the fabric sample that it isn't constructed very well with raised surfaces and irregular lines. This may have a bearing on the test results.

Sample 4 below (fig 61) is the 350 denier X-Static, again with virtually every pick being X-Static.

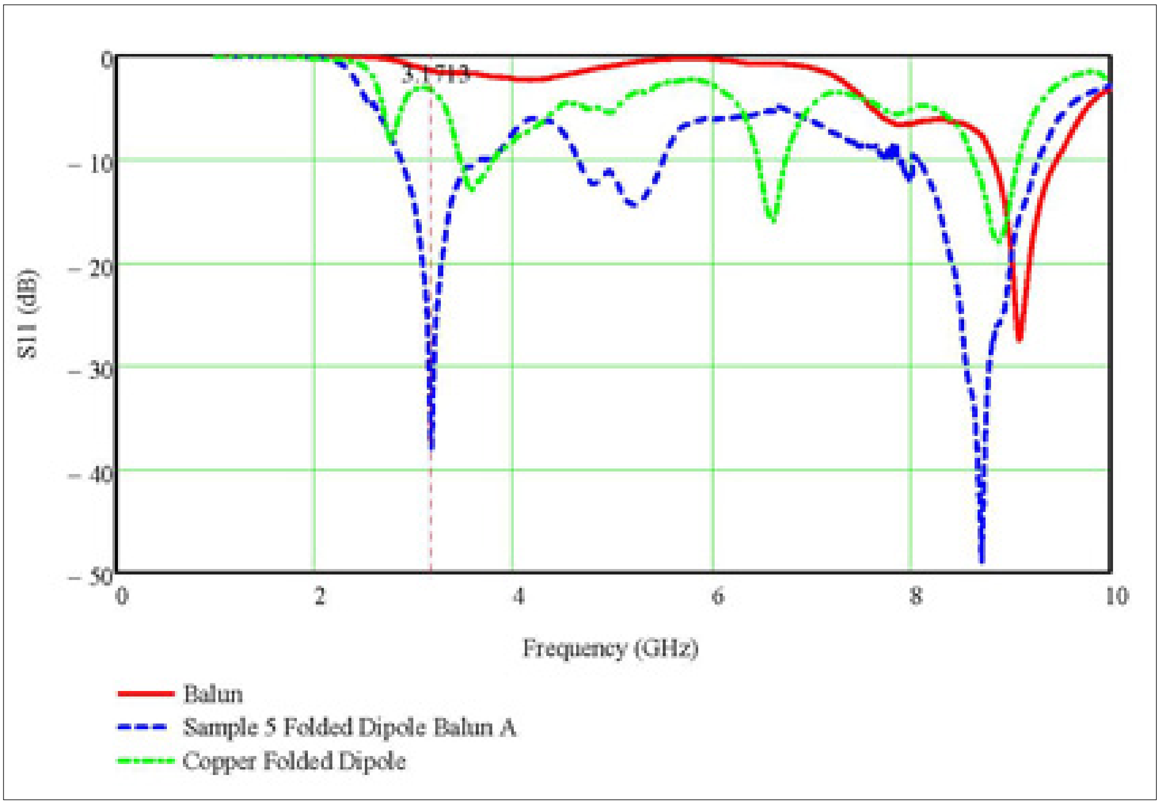
This too is showing a lossy antenna.

Fig 61 Printout of test result of a fabric folded dipole and copper folded dipole.



The test results of sample 5 (fig 62) below show encouraging signs. This was constructed of 280 denier X-Static at alternate picks.

Fig 62 Printout of test result of a fabric folded dipole and copper folded dipole.



This appears to be the most successful sample. The troughs are close together and it is not as lossy as the other samples tested.

3.7.5 TEXTILE FOLDED DIPOLE ANTENNA CONCLUSION

The results that were given indicate that there is a long way to go with the folded dipole antenna. Although encouraging signs are evident, on the whole they are not promising which may have something to do with the following contributing factors. The connection from the Balun to the fabric antenna may be unreliable. If a firm and true connection is not achieved, this could well have a bearing on the actual measurements being given.

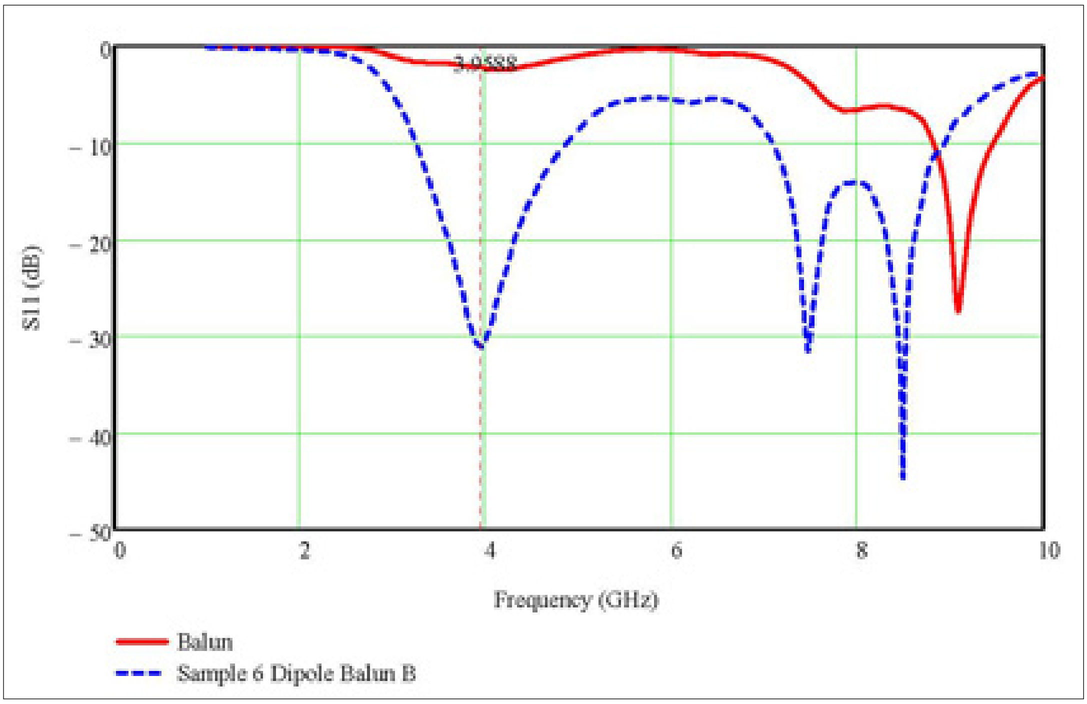
Secondly, the shape of the woven antenna may not be helping. The images have shown that the woven folded dipole is not of a uniform structure. The raised surface on the vertical planes and the curved nature of the horizontal planes may give unreliable readings. Due to the inaccuracies and problems that occur during the weaving process, the folded dipole would not be a viable option to pursue.

The antenna needs to be reproduced faithfully every time and to the given specifications. These initial samples have proved that for this antenna it is not possible.

3.7.6 DIPOLE TEST RESULTS

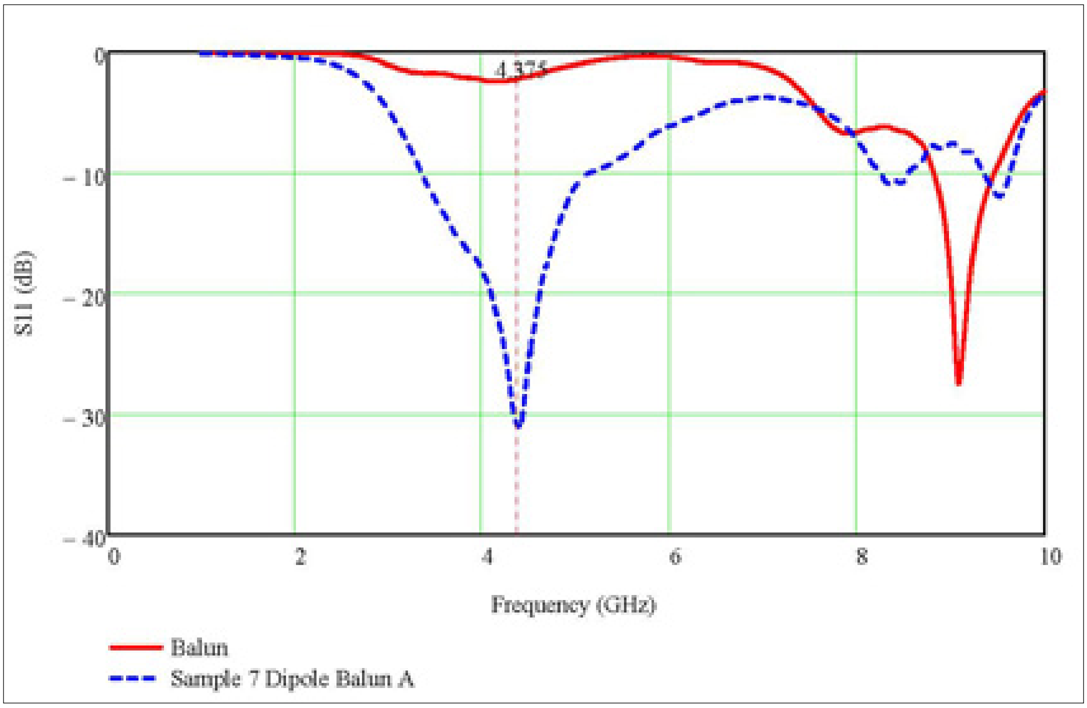
The following measurements (Fig 63 - 65) show the results for the Dipole antenna. The layout is similar to that of the folded dipole results. It is the blue dashed line in comparison with the red line that is of importance.

Fig 63 Printout of test result of dipole antenna



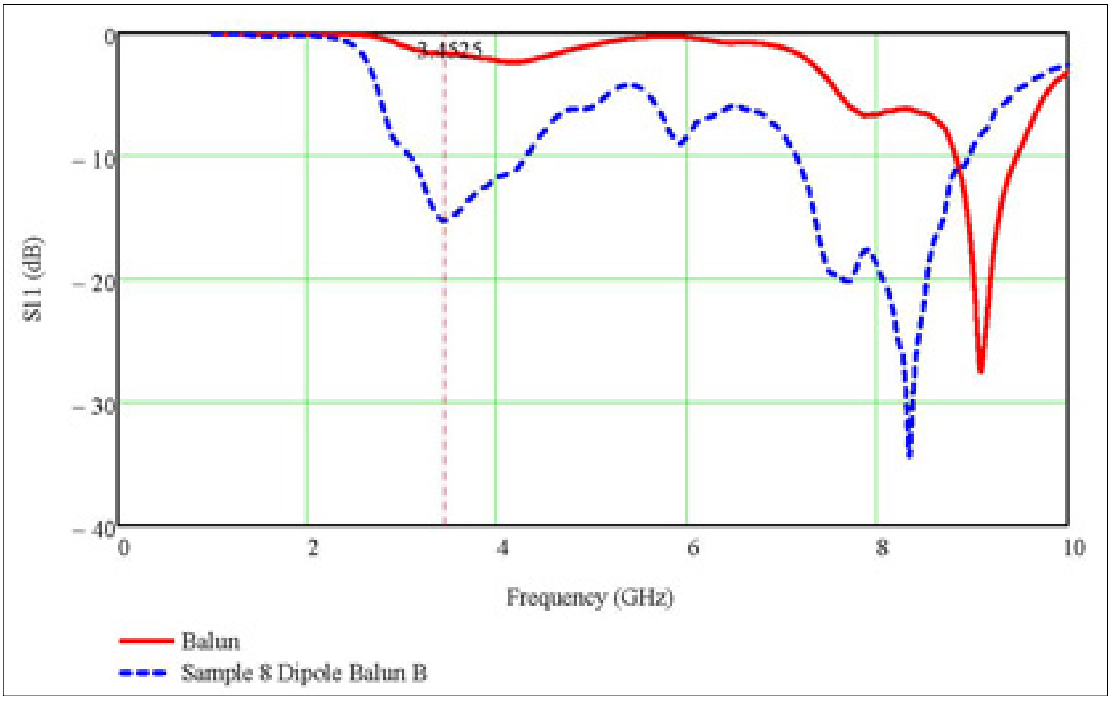
The image is showing the result from the 280 denier X-static. It is displaying encouraging signs but it still remains lossy.

Fig 64 Printout of test result of dipole antenna



The result above is for the 350 denier X-static. Below is the result for the 170 denier X-Static. Results do indicate that there is some activity from the antenna. The down side is that the antenna displays irregularities in the production and also the need for 2 additional wefts could be problematic. The design of the antenna doesn't lend itself to be replicated easily.

Fig 65 Printout of test result of dipole antenna



3.7.7 TEXTILE DIPOLE ANTENNA CONCLUSION

The conclusion of both the textile Dipole and Folded Dipole are very similar. The test results show there are some encouraging signs of it resonating but overall they are very lossy.

With both the Folded Dipole and the Dipole there is one major question that would needed to be answered, should they have been successful, would they have been able to be reproduced using modern mechanical weaving processes? There were many problems encountered during the production of the Antennas using the floor loom. The introduction of 2 additional wefts is time consuming when weaving and the images show the irregularities in them. Each image has differing irregularities which clarifies that they cannot be reproduced faithfully every time. These specific antenna designs have shown that they are not the easily replicated with the use of weaving. Embroidery could give a more positive outcome if these were to be investigated again.

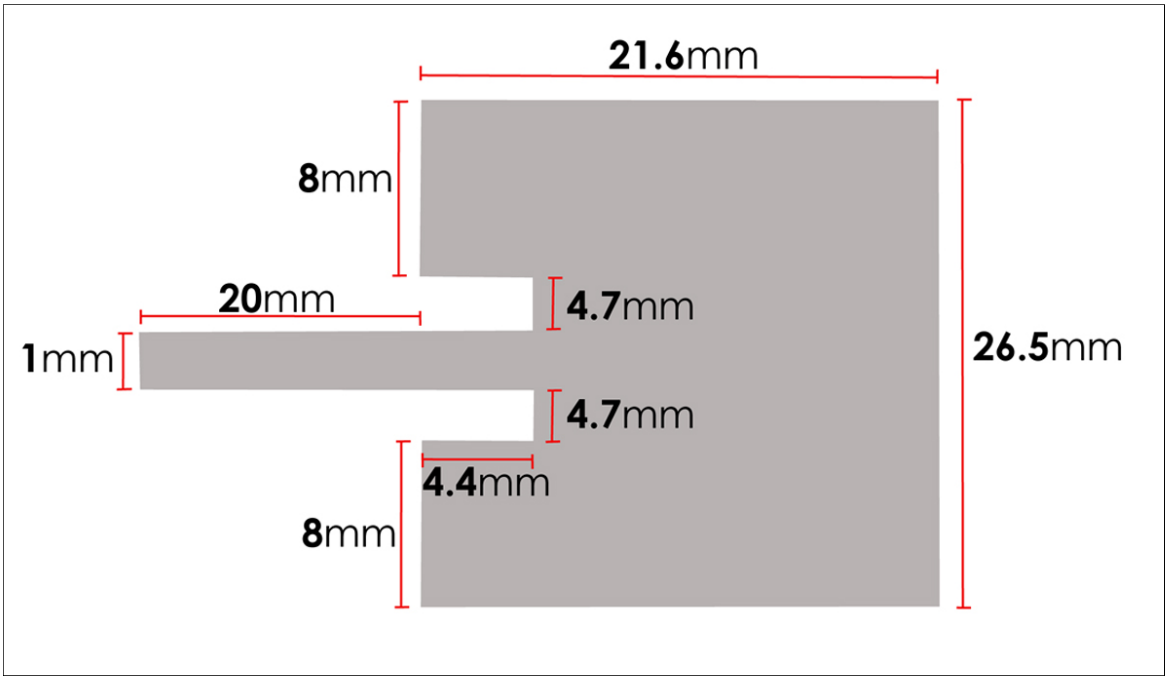
3.8 DESIGN AND PRODUCTION OF A FABRIC PATCH ANTENNA

A patch Antenna was designed by department of Electrical Engineering.

Both the surrounding cloth and the antenna were woven using a plain weave structure. This still seemed the most reliable structure to facilitate the antenna due to its strength and how close the yarns could be woven in relation to one another.

The illustration below shows the antenna design with the dimensions required. Working with a different medium, yarn instead of copper, could mean that the specific sizes may not be exact. The actual woven sizes are displayed in the table.

Fig 66 Illustration of a patch antenna supplied by the department of Electrical Engineering at Loughborough University, not to scale



The cloth was woven with a 2/30s cotton at 48 ends per inch.

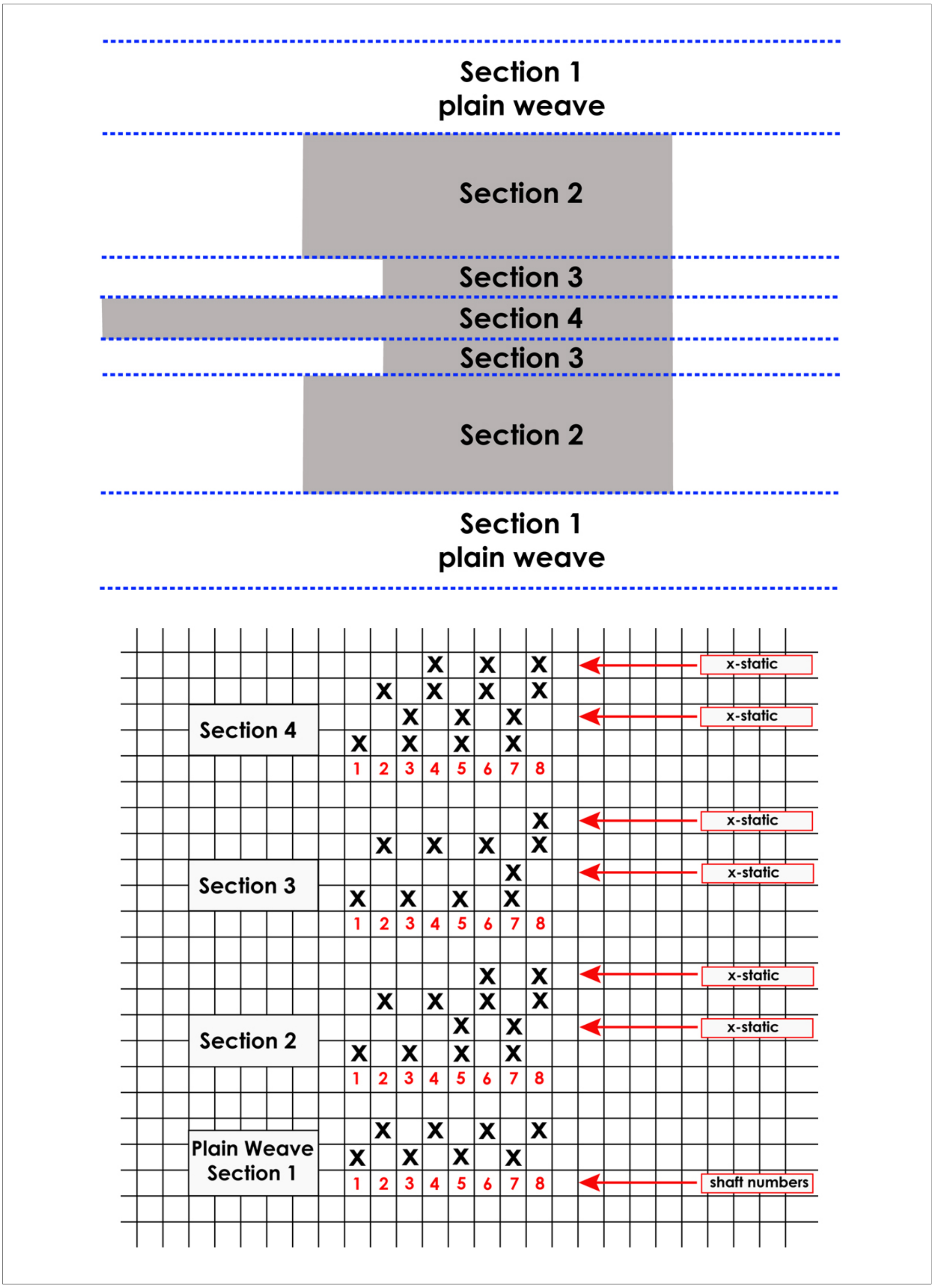
A 4s spreader was used with 12 ends per dent. The reed was a 24s reed with 2 ends per dent but with the first 4 dents having 3 ends per dent.

The conductive X-static yarn was introduced into the weft as alternate picks to the cotton

To make the weaving lifting plan easier, the antenna was divided into sections 1, 2, 3 and 4.

This can be seen in the image overleaf along with the lifting plan which shows the 4 sections and also indicates where the X-Static was introduced.

Fig 67 shows the patch antenna divided into sections along with the lifting plan which illustrates the 4 sections and also where the X-static was introduced.



The table shows the 3 patch antennas were sampled. The information gives the number of picks used in each section and also the required measurements and the final realised measurements.

Antenna sample	170 Denier	280 Denier	350 Denier
Picks in section 2	12	12	10
Picks in section 3	6	8	6
Picks in section 4	2	2	2
Required height & width of section 2	Height – 8 mm Width – 21.6 mm	Height – 8 mm Width – 21.6 mm	Height – 8 mm Width – 21.6 mm
Realised height & width of section 2	Height – 8.5 mm Width – 21.5 mm	Height – 8.5 mm Width – 21 mm	Height – 7.5 mm Width – 21.5 mm
Required height & insert width of section 3	Height – 4.7 mm Insert width – 4.4 mm	Height – 4.7 mm Insert width – 4.4 mm	Height – 4.5 mm Insert width – 4.5 mm
Realised height & insert width of section 3	Height – 4.1mm Insert width – 3.5 mm	Height – 4.7 mm Insert width – 4 mm	Height – 4.7 mm Insert width – 4 mm
Required height & width of section 4	Height – 1 mm Width – 20 mm	Height – 1 mm Width – 20 mm	Height – 1 mm Width – 20 mm
Realised height & width of section 4	Height – 1 mm Width – 18 mm	Height – 1 mm Width – 16 mm	Height – 1 mm Width – 17 mm

As can be seen from the table, the dimensions of the textile patch antenna (Fig 68) are very good in comparison with the required sizes. The slight differences in size were not a cause for concern.

Fig 68 Image of a woven patch antenna produced on a Dobby Loom. Authors own photograph

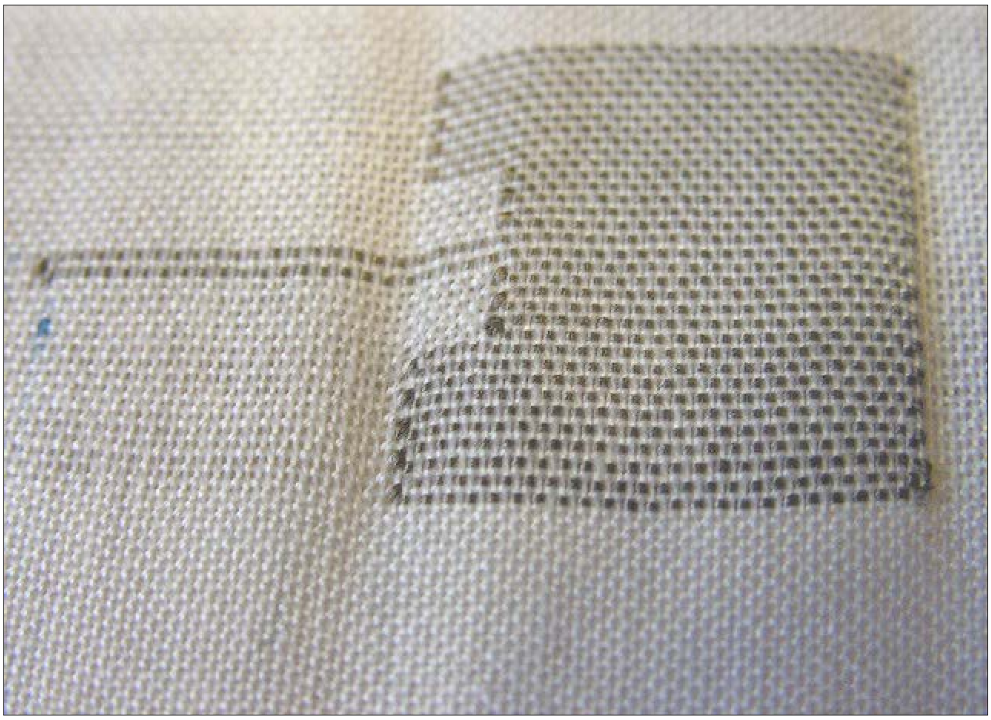
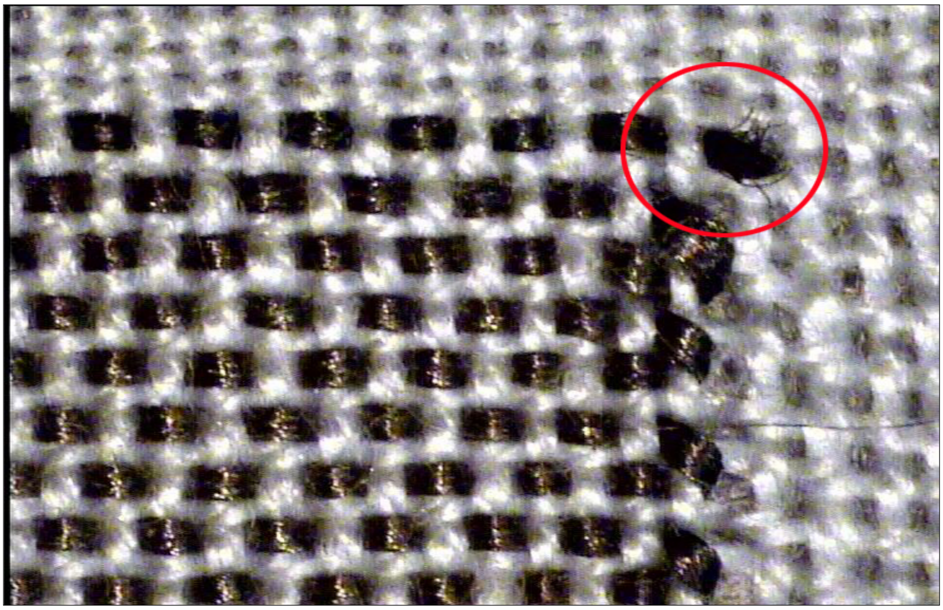


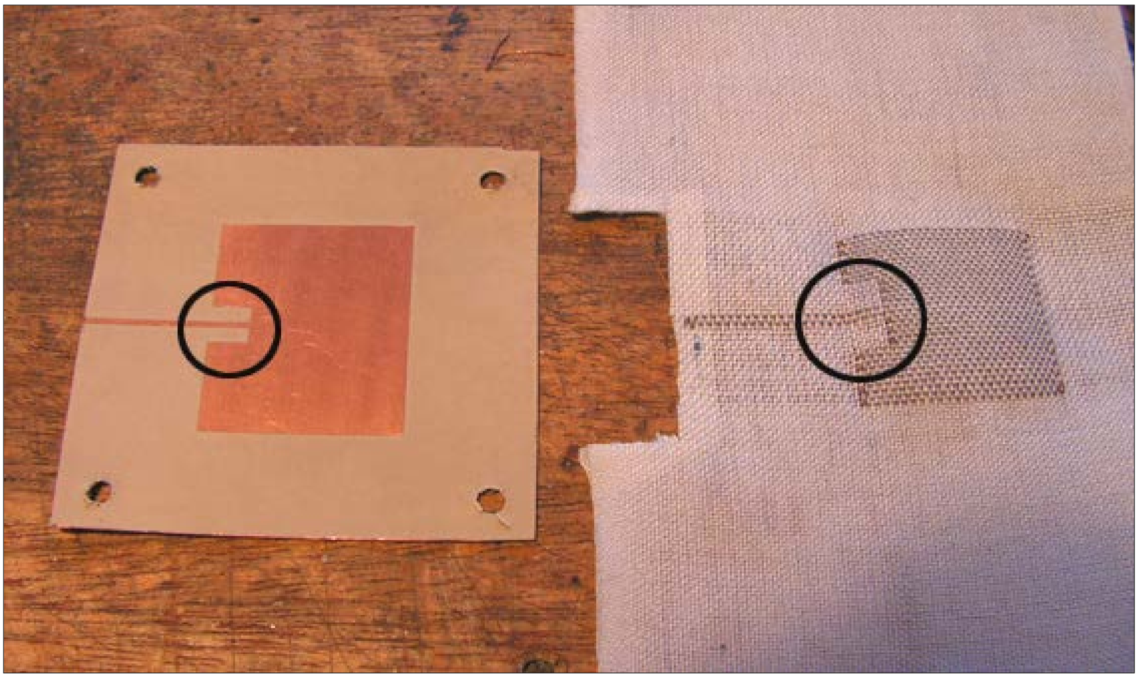
Figure 68 shows how much better the patch antenna sits within the fabric as opposed to the previous experiments with the dipole and folded dipole antenna. The overall look of the antenna is uniform and is very encouraging. A negative aspect of this though is the manner in which the antenna is finished in the corner. This can be seen in Fig 69 where the red circle highlights this. The yarn is just cut which leaves an unfinished end. This could lead to the yarn coming loose or fraying.

Fig 69 the red circle indicating the finish of the woven antenna



The sections circled in black on fig highlight the areas where there is a slight discrepancy with the dimensions. This however shouldn't have any negative bearing on the test results.

Fig 70 Image showing a conventional copper patch antenna and a woven patch antenna for comparison, Authors own photograph



The design of the antenna allowed the X-Static yarn to be introduced to the cloth far easier as there were no awkward shapes to contend with. The antenna was sampled using the 3 deniers of X-Static, 170, 280 and 350. All 3 yarns gave exceptional results. The design was easier to weave and replicate and the aesthetics were better that the previous sampled antennas.

Once the fabric patch antennas had been sampled, the testing was carried out.

3.8.1 FABRIC PATCH ANTENNA TEST PROCEDURE.

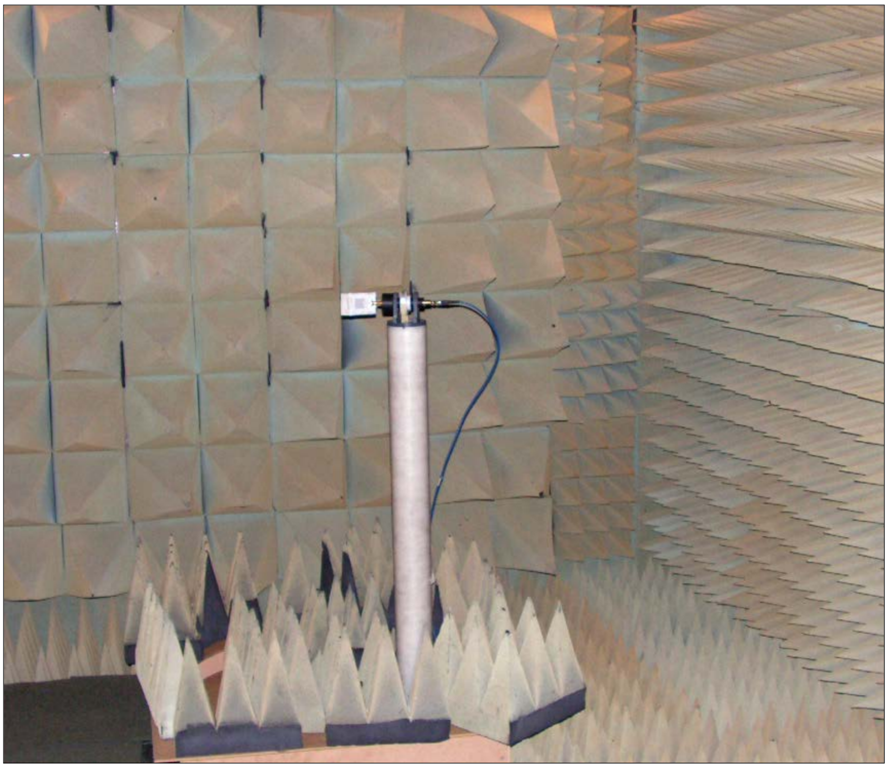
The textile patch antennas were tested using the waveguide analyser and also tested in the anechoic chamber which is situated within the department of Electrical Engineering at Loughborough University. It is vitally important to test the samples in the chamber. The following section explains the importance of it.

3.8.1.1 Anechoic test chamber

To gain a more reliable test outcome, it was important that the test procedure was carried out in the controlled environment of the chamber Fig 71

The anechoic chamber is designed in such a way that it stops reflections of either sound or electromagnetic waves. It is also insulated from exterior sources of noise. This combination means that the chamber simulates a quiet space of infinite dimension. This is important as the results couldn't be influenced by any exterior sources which in turn would assist in giving false results.

Fig 71 Image showing part of the anechoic chamber used to test the fabric patch antenna, which can be seen in the centre of the photograph positioned on the equipment prior to testing. Authors own photograph



The internal appearance of the anechoic chamber can appear strange to someone who isn't familiar with either acoustic or radio frequency testing. The surfaces of the interior differ between the 2; the radio frequency chamber which was used is covered with radiation absorbent material whereas the other has acoustically absorbent material. The anechoic test chamber at Loughborough University houses the equipment to measure the performance of antennas and the radiation patterns.

The previous image shows the radiation absorbent material (RAM) surrounding the test equipment. It is in the form of different sized pyramid shapes, which is deemed to be the most successful shape. Its construction is made from a type of rubberised foam mixed with controlled measures of carbon and iron.

It is designed and shaped in order to absorb any unwanted radio frequency radiation as effectively as possible and from as many directions as possible. The more effective the RAM, the level of reflected radiation will be less. It is imperative that when the measurements are being taken under test conditions, there are as least amount of potential external contaminations as possible that may in turn give errors in the measurements.

Much of the testing and supporting equipment used with in the chamber, where possible, has to expose as few metallic surfaces as possible as this would cause unwanted reflections. Often the equipment used is made from non-conductive plastic and wooden structures/components in order to alleviate this problem.

It is also not permitted for anyone to be in the chamber during the test procedure. This would not only cause unwanted reflections from the human body but also there is the potential of radiation hazard should any tests be performed at high radio frequency powers.

3.8.2 FABRIC PATCH ANTENNA TEST RESULTS

Whilst the fabric antenna in the anechoic chamber is being measured, it also oscillates. This is in order to gain the measurements from various angles to illustrate the radiation pattern and to see if it is working efficiently.

Fig 72 Print out showing the results of the woven patch antenna and a copper patch antenna

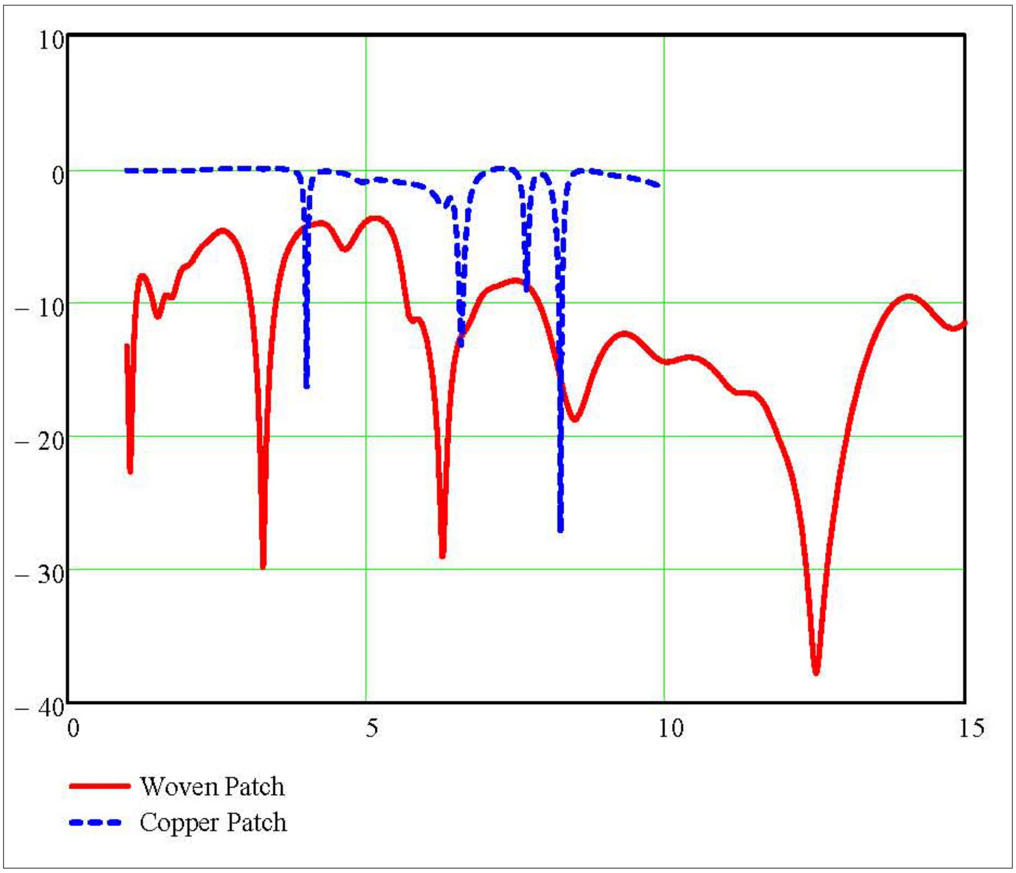


Figure 72 shown above indicates the measurements of both the woven patch antenna, and also the standard copper patch antenna.

Again with the results, it is important to see if the woven antenna is achieving the similar troughs as the copper antenna. This would indicate that the cloth sample is beginning to show characteristics of a conventional copper antenna.

The image above shows that there is a similar pattern from the woven and copper antenna.

Figure 73 shows the 280 denier patch antenna. The performance is not as good as would be hoped as can be seen from the differing troughs between the 2 samples.

Fig 73 Print out showing the results of the woven patch antenna and a copper patch antenna

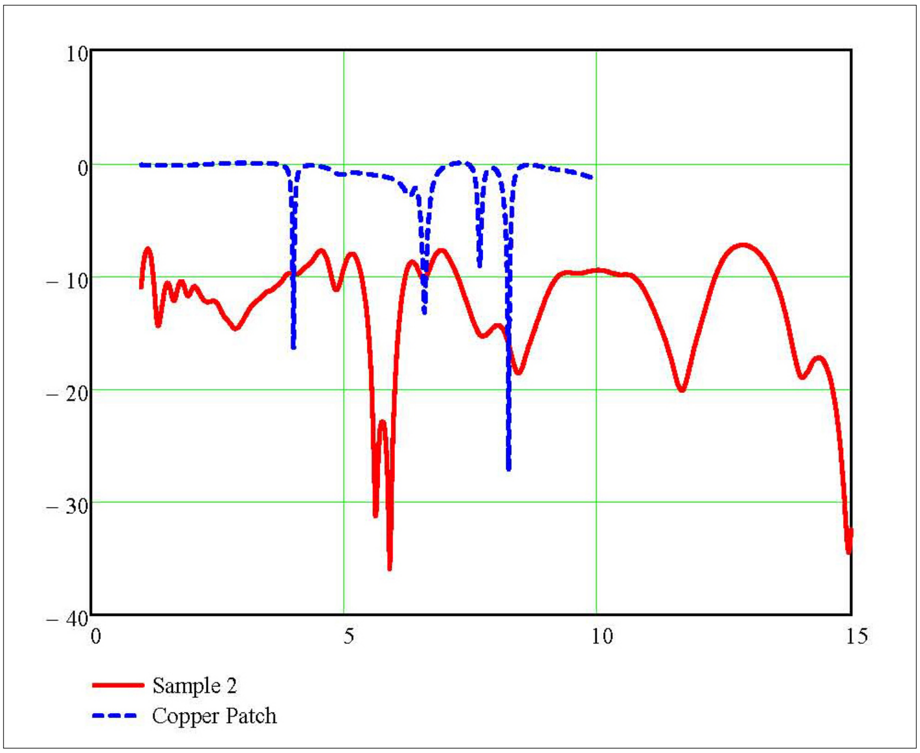


Fig 74 Printout of the H and E plane measurements of the Copper and woven patch antenna

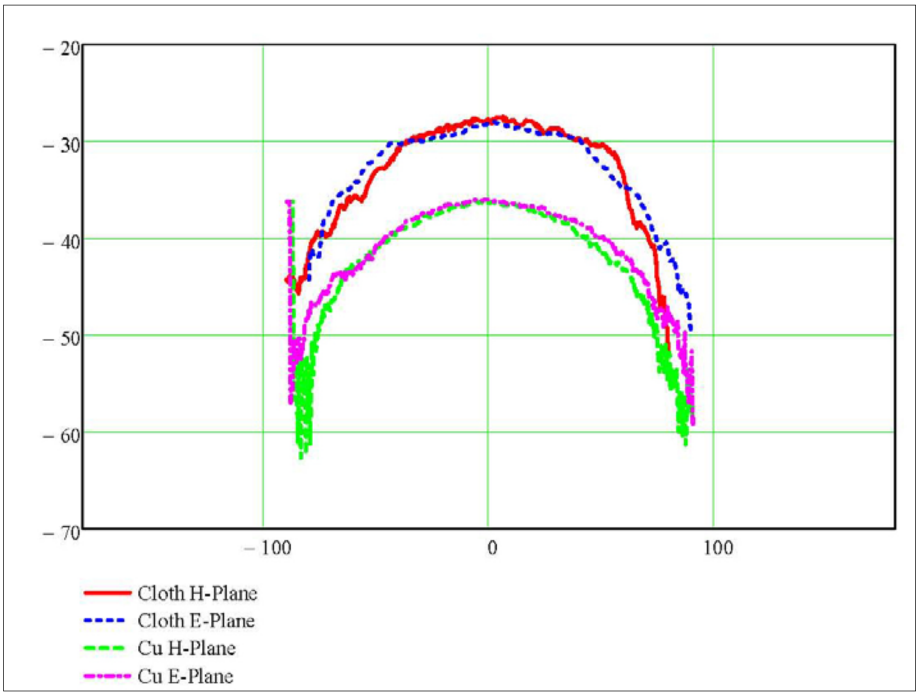


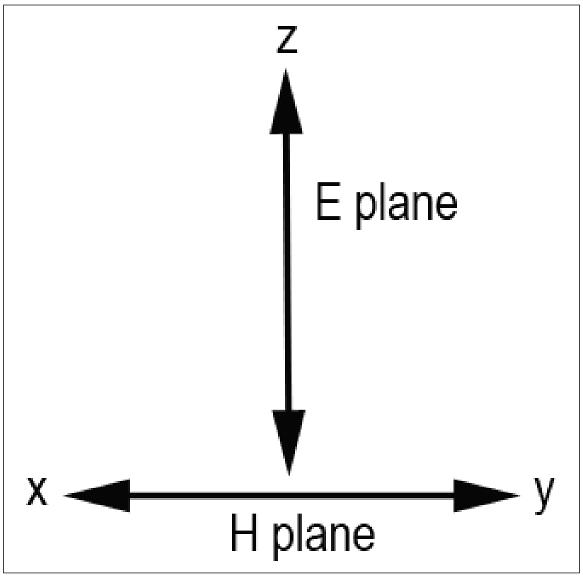
Figure 74 above, illustrates the measurement of the H plane and the E plane of both the cloth antenna and the copper antenna, illustrated with the scientific abbreviation Cu.

What is encouraging about the above measurement is that shape is very good.

3.8.2.1 The H plane and E plane

The H plane and the E plane are measurement planes (Fig 75) and can be simplified down for understanding.

Fig 75 Image showing the measurement planes
Authors own illustration

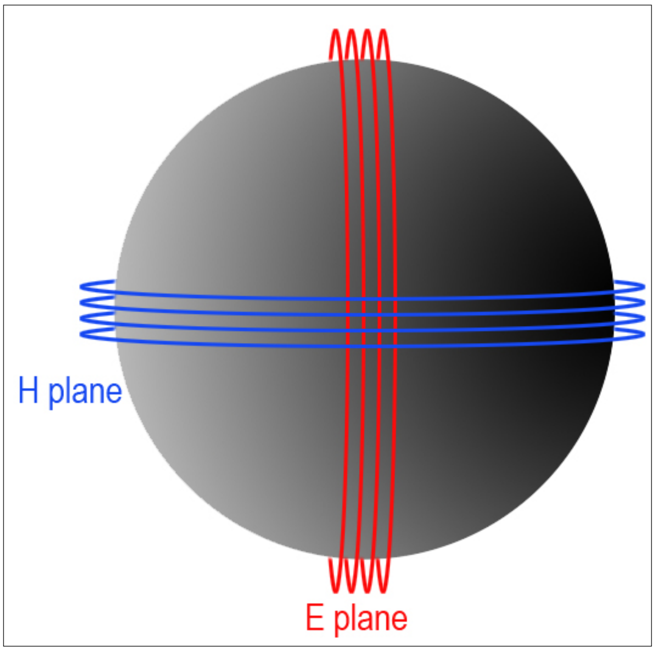


The H plane contains the magnetic field vector and also the direction of maximum radiation. This plane coincides with the horizontal plane and it lies at a right angle to the E plane. It takes the measurements from X to Y. Technically; this is known as the Azimuth plane, an angular measurement in a spherical co-ordinate system.

The E plane contains the electric field vector and this determines the orientation of the radio wave. This is the direction of measurement Z, the elevation measurement, up and down. The E plane and H plane should be 90 degrees apart.

To help illustrate this better, figure 76 overleaf, is a very simplified model of how the measurements are taken.

Fig 76 Image showing how the H and E plane measurements are taken,
Authors own Illustration



The measurements are taken at set degree intervals both horizontally and vertically, on the H plane and the E plane. The measurements are taken over the whole of the sphere shape and not just the lines indicated on the illustration.

Further measurements can be found in the appendices.

3.8.3 Patch Antenna result summary.

From the measurements gained of the manually woven patch antenna, it is apparent that the antennas are lossy.

What this implies is this, there is a lot of power going into the antenna but it is being dissipated or lost. This in turn causes an antenna to be lossy. This could be down to the poor construction of the antenna with there not being enough surface coverage of the conductive yarn. Being an alternate pick, the level of conductivity has been compromised, although the appearance of the antenna is considerably better.

Along with this, when the antennas were measured, the ground plane may have been on the small side. The ground plane plays an important part as a reflector or director for an antenna.

If the sample antennas were tested again but using a larger ground plane, the results may have been more satisfactory.

It is apparent that there is a certain degree of activity with the textile antenna and with further work, the performance could be increased.

It is important to have a loss less, or as near as, antenna as this has a bearing on the performance. The more power being absorbed results in a stronger signal being sent.

From the initial conception of the idea of producing a textile antenna, it was an important factor that the antenna could be produced on industrial weaving machines as well as manually operated floor looms.

3.9 PATCH ANTENNA PRODUCED BY CASH'S

For the research project to be successful it was important that any antenna could be replicated reliably using modern production methods. A Coventry based company called Cash's was approached. Cash's were experts in precision weaving and they under took the weaving of the same patch antenna that the Author had previously woven by hand.

The objective was to produce a stable antenna that had better measurement results than previous samples woven using a hand operated floor loom.

The antennas were woven on a Bonas 6 space Varitex Needle loom with a Bonas EJI 512 hook Jacquard (Electronic jacquard). The loom has a series 200 loom controller.

The images below show the 2 Antennas produced as a comparison. On the left (fig 77) is the patch antenna produced on the dobby loom by the Author. On the right (fig 78) is the patch antenna produced by Cash's.

Fig 77 antenna designed by the author

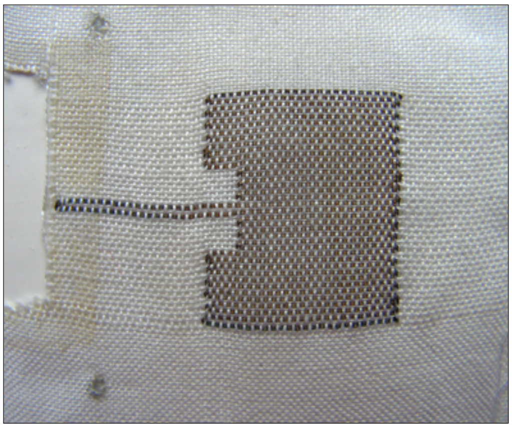


Fig 78 antenna designed by Cash's

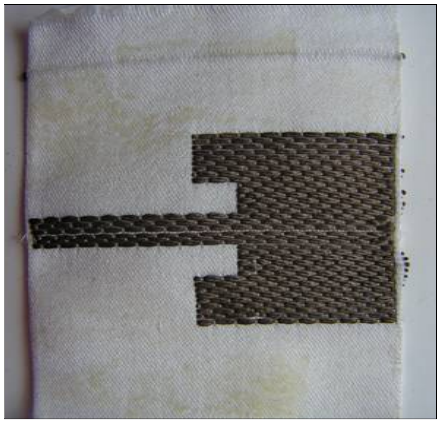
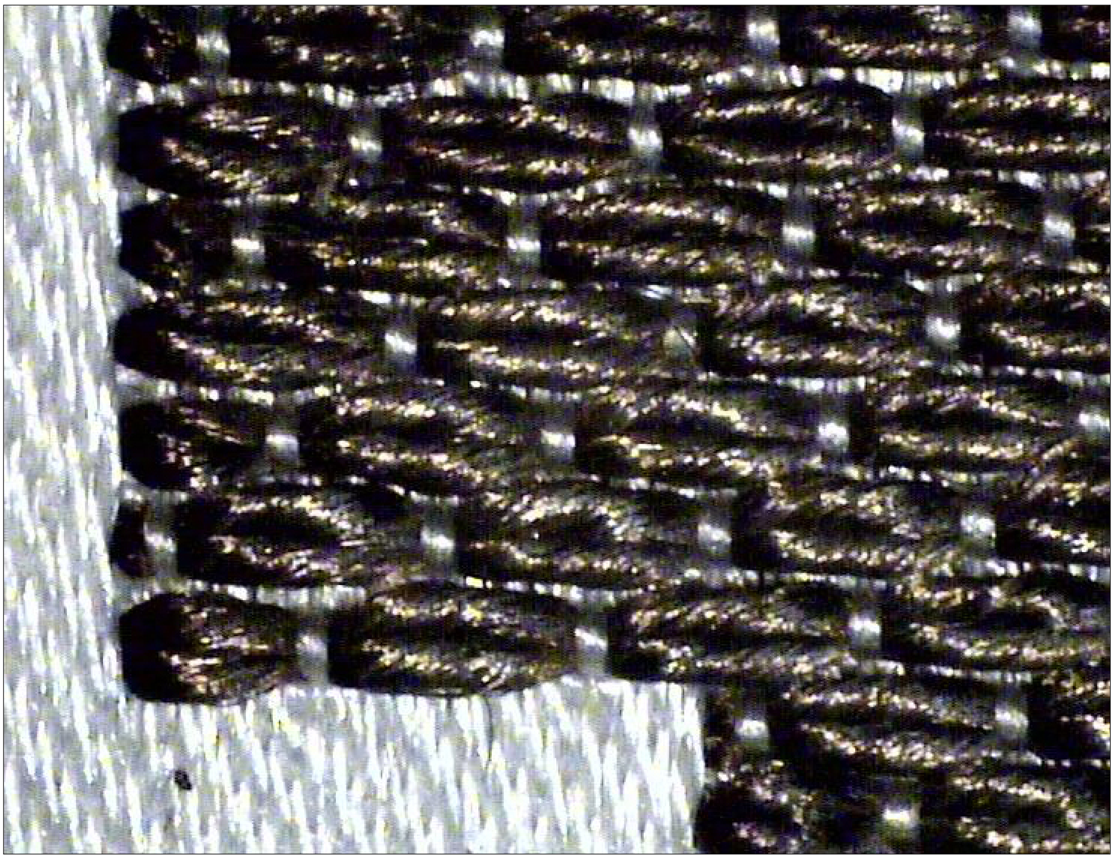


Fig 79 shows a close up of the woven antenna produced by Cash's. The twill structure is clearly seen and also where the weft is bound.



As the image demonstrates, the structure for the antenna produced by Cash's was different to that of the one produced by the Author. There were 118 ends per cm, 27.5 picks per cm. The ground is a twill, the information from Cash's was that the structure is a 4/1 warp faced twill. The antenna was woven as an extra weft and is bound every16 ends.

With having used 2 different structures to weave an antenna, it would be an interesting contrast to see if one gave better results than the other. If so, would it be down to the structure or the fact that it was woven on an industrial machine?

If the images are examined, the sample from Cash's looks quite promising from the face side. On the reverse it shows that the x-static yarn has what could be described as, incomplete yarns. It is unclear on the wider picture if this has any negative bearing on the results that were given once it was measured.

At this point, prior to any measurements being taken, it is promising to see that it has been possible to weave a patch antenna by using industrial weaving looms. The measurements, in terms of actual size, of the Cash's sample are almost identical to that of the samples previously produced.

3.9.1 Measurement results of samples produced by Cash's

The samples produced by Cash's were also tested in the anechoic chamber at Loughborough University.

The images below (Fig 80 - 83) show the radiating patterns of the vertical plot, or the E-Theta, and the horizontal plot, or the E-Phi.

From the findings of the dept of Electrical Engineering, it was noted that the performance of the antenna was not as successful as hoped.

Fig 80 Image showing the radiating pattern of the vertical plot at 2000MHz

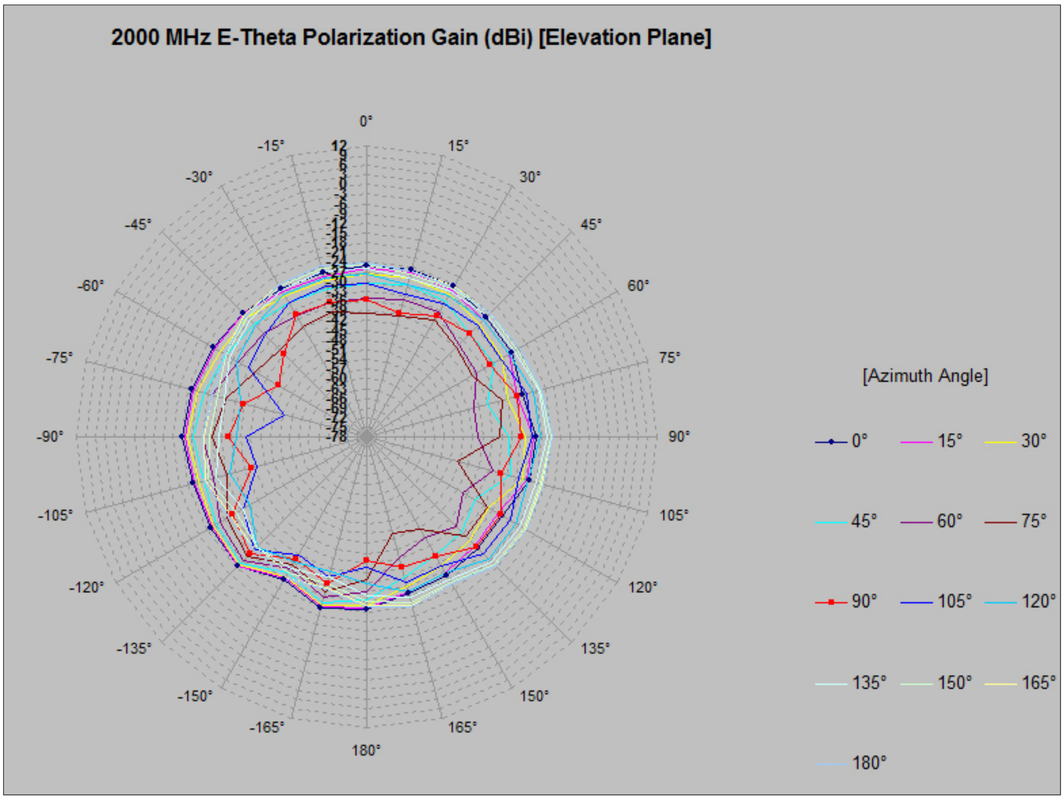


Fig 81 Image showing the radiating pattern of the horizontal plot

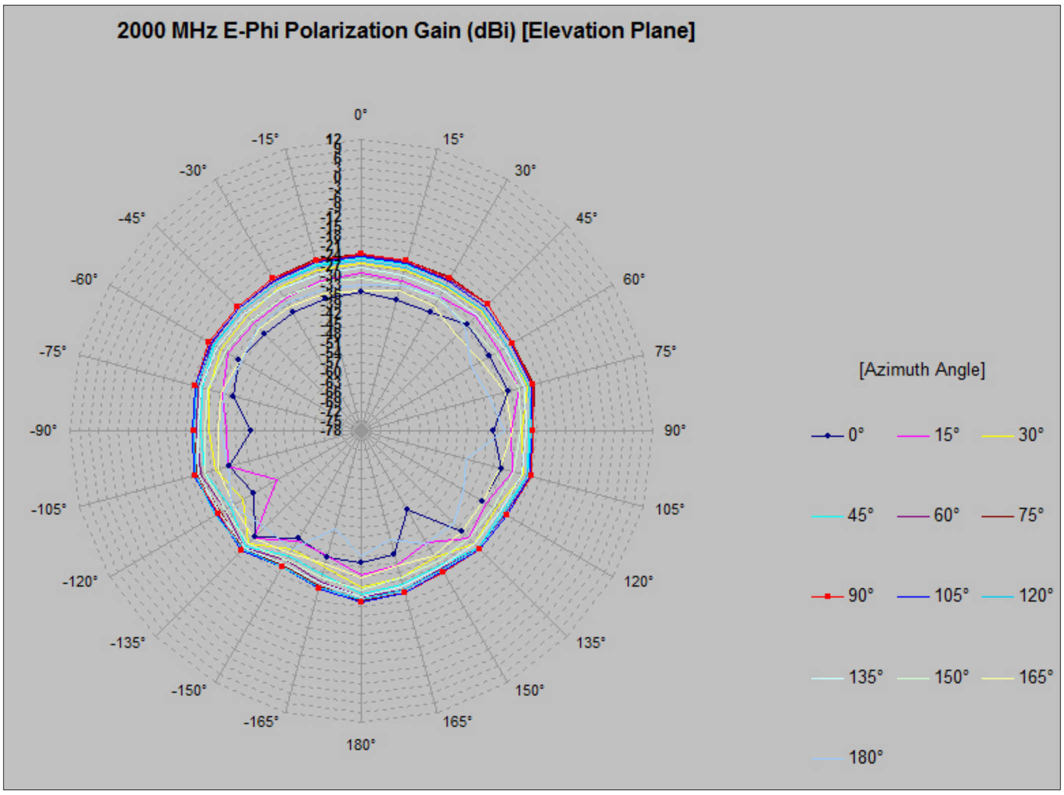


Fig 82 Image showing the radiating pattern of the vertical plot at 4000MHz

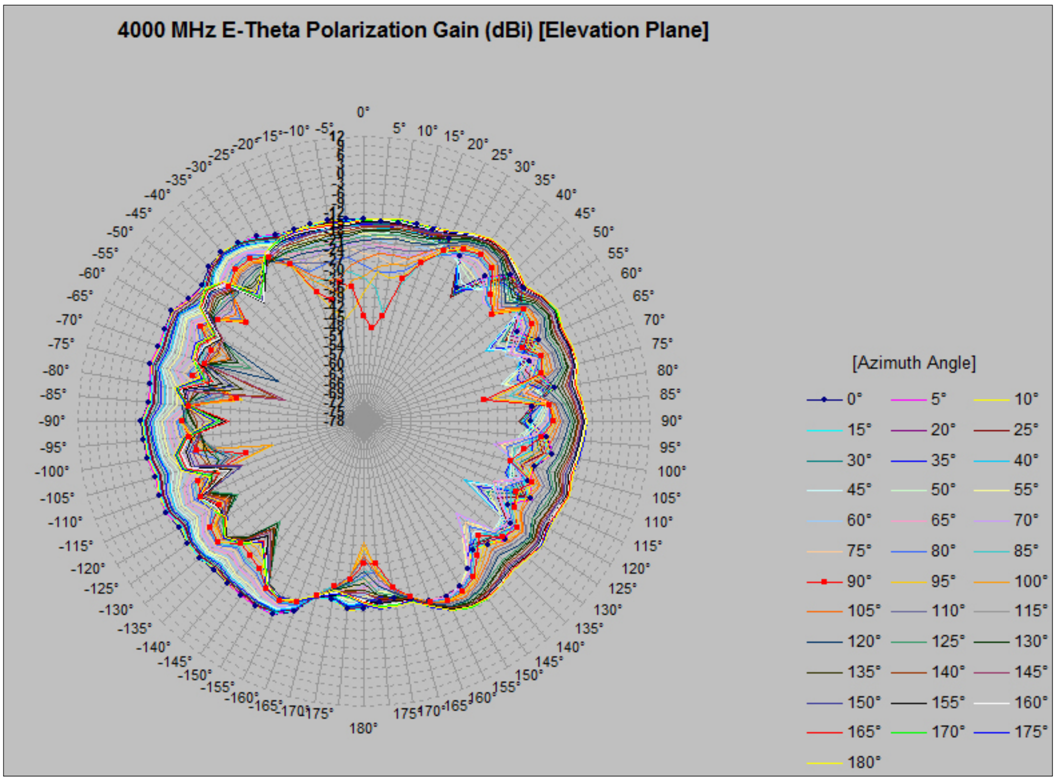
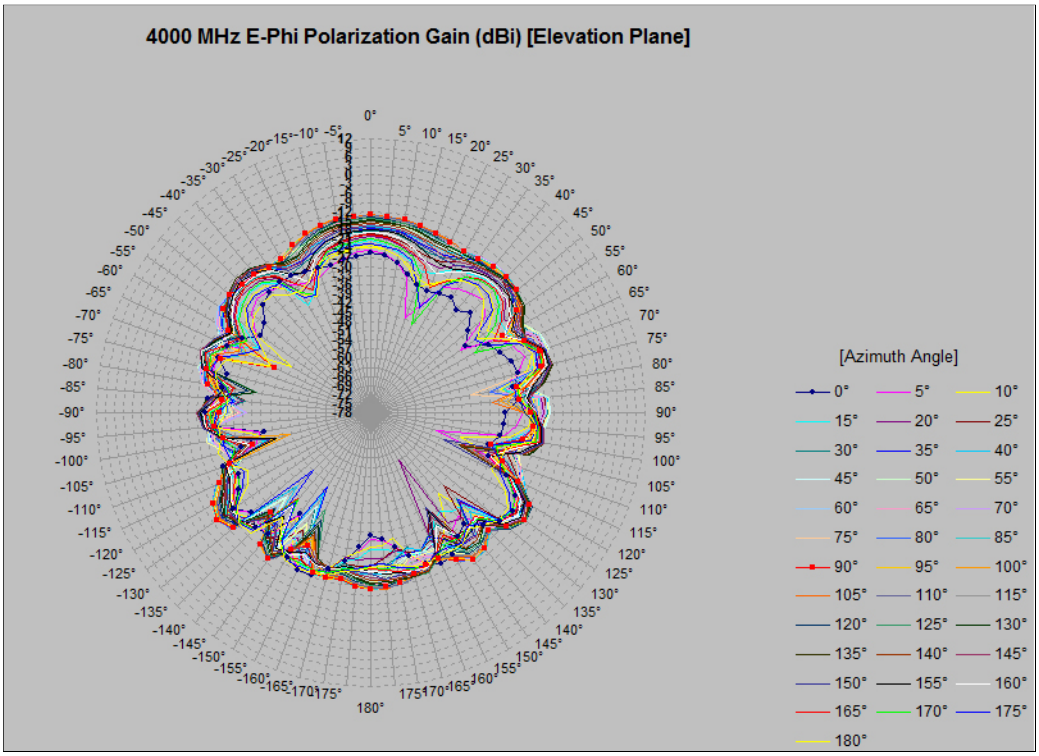


Fig 83 Image showing the radiating pattern of the horizontal plot at 4000MHz



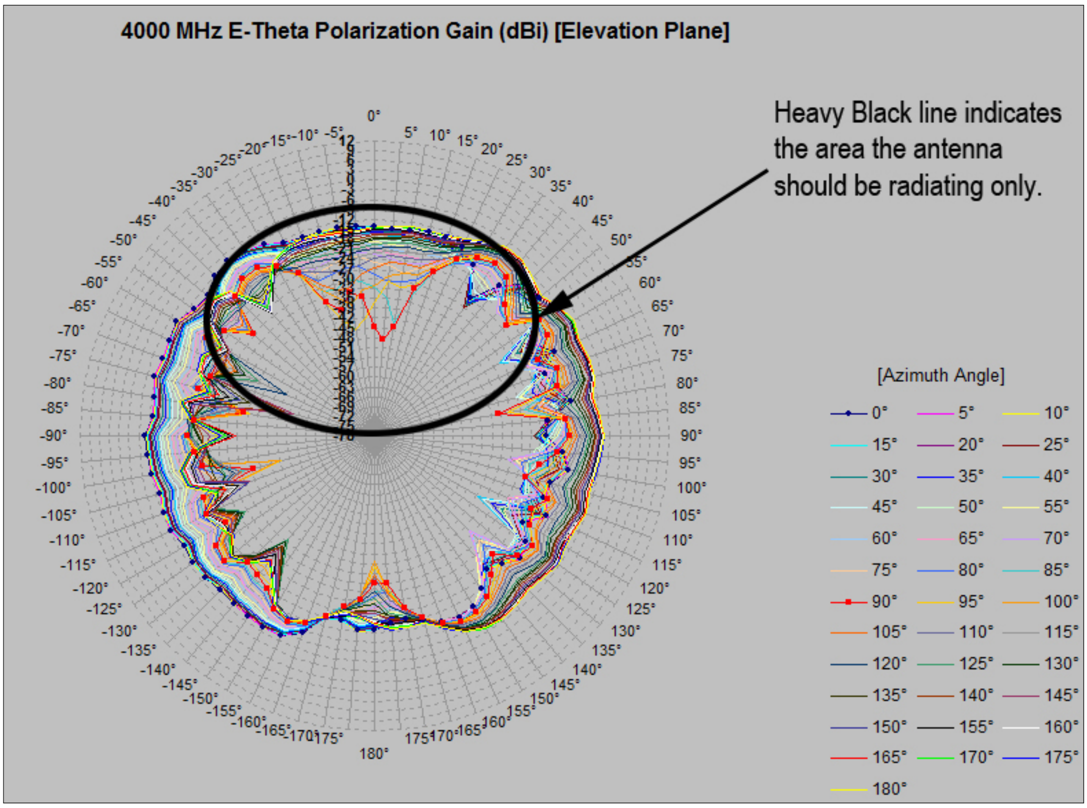
The 2 sets of results are taken at 2000MHz and 4000MHz. Other results can be found in the appendices. The numbers around the circle indicate at what degree a measurement was taken. This illustrates the point that Author previously made when describing the H and E plane.

Please refer to the next image overleaf, Fig 84 for a simplified explanation of the results.

3.9.1.1 Understanding the result

As previously mentioned, the images show the radiating/resonating pattern of a textile patch antenna. A perfect patch antenna with good gain (radiation) should really only radiate in the area shown on figure.

Fig 84 Image showing an explanation of results



The solid black line is only giving an indication of the area that one would expect to see the pattern. Also the shape would be similar to the one shown but with the bottom half of the plot being smaller.

As with the results shown for the hand produced antenna, these are showing that the antenna is lossy. Again the power is going in but being lost and not radiated out. Possible reasons for this, again a poorly constructed antenna, not enough solid conductivity. Gaps within the yarn once woven could be a cause of this. If the yarns aren't connecting with one another, reliable conductivity is compromised. The ground plane could also be a contributing factor to the poor performance.

3.9.2 Summary of results

The results for the patch antennas produced by both the Author and Cash's have shown at some points, that there is some resonation taking place. The positives to take from this are that it has been possible to replicate a patch antenna manually and mechanically. On the negative side, the performance of the antennas has not been as successful as it would have been hoped.

With this is the option of re-testing with a larger ground plane, or re-assessing the woven structure used to construct the antenna. These actions may have a positive bearing on the outcome of the antennas.

Results from this and all other measurements can be found in the Appendix.

Along with the construction of textile antennas, Textile transmission lines were to be investigated. These were produced in collaboration with Thomas Hill from the Department of Electrical Engineering at Loughborough University.

4 TRANSMISSION LINES

An antenna woven into cloth alone would not work without a power supply, a means of transferring power to the antenna is vital. The power supply was never going to be considered during the period of research, only the antenna and simple transmission lines. The initial sample transmission lines were woven by the Author and they were tested in the department of Electrical Engineering at Loughborough University.

4.1 The purpose of Transmission lines

The transmission line has only one purpose and this applies to the transmitter and the antenna. Transferral of energy output from the transmitter to the antenna with the least possible power loss.

To simplify even further, it is designed to guide electrical energy from one point to another.

Generally the energy cannot travel through normal electrical wire without experiencing great losses of energy. This is why the transmission tests were carried out using the X-Static yarn to gauge the suitability for use with the transmission lines as well as the antennas.

An antenna can be connected directly to the transmitter but for the most part, they are located some distance away from it. This is why there is the need for a transmission line.

How well the transmission line performs is determined by special physical and electrical characteristics, impedance[64] and resistance[65], of the transmission line.

Basic transmission line theory states that a transmission line in its basic form is made up of 2 conducting strips/wires on which electrical data or signals propagate. A perfect transmission line would have no attenuation[66] or insertion loss[67]. This would be virtually impossible to achieve. To get close to something that would be deemed to have the ideal characteristics, low loss materials are used. This would be the use of efficient conductors and good insulator dielectrics.

The most common transmission line configurations used are twin line, coaxial line, micro-strip line, coplanar wave guide (cpw), slotline and rectangular waveguide.

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[64] impedance describes a measure of opposition to alternating current (AC)

[65] Electrical resistance is a measure of the degree to which an electrical component opposes the passage of current

[66] attenuation affects the propagation of waves and signals in electrical circuits

[67] A loss of power, negative gain.

4.2 Problems with Transmission lines

One particular problem could be the close proximity of the conductivity to the human body. This also applies to the construction of antennas. Consideration of this is important when working with conductivity so close to the body. This however was a delimitation within the research programme and was not be looked at during these investigations.

The body has a natural ability to conduct electricity and therefore it will serve as a relatively good conductor. This is mainly due to the body comprising of nearly 80% water, amongst other things, and this makes it a fairly efficient path for electricity to pass. The water has 'impurities' within it which make up the fluids of the body. It is these impurities that further enhance the body's electrical conduction capabilities. The skin however is a very lossy material, which means it doesn't have the qualities to transfer power and acts as a form of insulation for the body when in close proximity with electrical implements. Sweat or grease though can inhibit the insulating characteristics of the skin.

Another thing to look for, in terms of losses, is that caused by radiation and induction.

The fields surrounding the conductors cause both. Induction losses occur when the electromagnetic field about a conductor cuts through any nearby metallic object and a current is induced in that object. As a result of this, power is dissipated in the object and is lost.

When it comes to radiation losses, this occurs because some magnetic lines of force around a conductor do not return to the conductor when the cycle alternates. The lines of force are then projected out as radiation and this in turn results in power losses. In simpler terms, the power is supplied by a source, but is not then available to the load.

4.3 Configuration of transmission line to be used

Researcher Thomas Hill decided that the type of transmission line configuration to be used was the coplanar waveguide.

One of the oldest and probably most common forms of coplanar waveguide is created when a conductor is separated from 2 ground planes but they all lie on a common plane mounted upon a dielectric[68]. Ideally the dielectric is infinitely thick, but with this not really being practical, it's only thick enough so that the electric field doesn't escape.

[68] A non conductor of electricity

There are numerous variations of the CPW (coplanar waveguide) configurations on the substrate, but another variant involves the alteration of the ground plane. A ground is formed on the underside of the dielectric; this then yields a grounded CPW or GCPW.

Coplanar waveguide is a very useful transmission line. This allows the mounting of components upon the circuit for ease of access. This configuration also supports very high frequency responses of up to 100GHz and above. This is due to there being no parasitic waves or odd modes being encouraged in the ground plane.

Although the CPW proves to be extremely useful and versatile, it does have its flaws. It isn't efficient when it comes to heat loss. This though can depend upon the thickness of the dielectric and presence of a heat-sink[69].

4.4 Adapting coplanar waveguide for weaving fabric circuitry

Coplanar waveguides work in a single plane and as a result have singular planar configurations such as GS (ground, signal) GSG (ground, signal, and ground) and GSSG (ground, signal, signal, and ground) parallel lines. These configurations work very well when they are mounted onto printed wire boards but as they were to be integrated into a textile substrate this would cause problems. In particular is the line dimension, which would have a tendency to alter due to the movement of the wearer. The dimensions between the lines would continually change but not with any regularity or particular pattern. The result of this would be that the line impedance[70] would change with every movement, causing reflections and parasitic waves (odd modes) to be produced.

Insertion loss would likely be considerable if parasitic waves were present. This in turn would be very detrimental to any signal produced. This movement of lines would be a hurdle to overcome if successful transmission was to take place.

The problems being encountered with this area are very similar to what could be experienced with the integrated textile antenna.

If conductive lines are in a single direction, excess capacitance[71] and inductance[72] are minimised. If only one yarn is used, the line width would be too small to actually transmit a signal. To overcome this, multiple lines would be woven and used in parallel. Unless these

[69] A protective device that absorbs and dissipates the excess heat generated by a system
[70] The opposition to the flow of alternating current in a circuit
[71] The property of a conductor that permits it to store charge
[72] A measure of the reaction of electrical components to changes in current flow by creating a magnetic field and inducing a voltage

lines were mated all the way along the length, cross talk could have an affect on the signal quality.

Cross talk is a term to identify a particular problem. A current carrying conductor produces an electromagnetic field that rotates around it in a helical formation.
When 2 or more conductors supporting current run near to one-another, they produce a coupling capacitance between them and an inductance which gives rise to cross talk.

Increasing the signal line width decreases the overall line impedance and also smaller distances between signal and ground lines, lowers line impedance. This in turn gives an element of control for trying to match the line when preventing reflections.
The proposed CPW configurations were determined by a computer simulation that decided the line thickness and spacing.
The sizes of the transmission line to be woven were as follows.
Length of all tracks was 40mm
The ground plane was 10mm thick.
The signal line was 5mm thick.
The spacing between each line was 1mm.

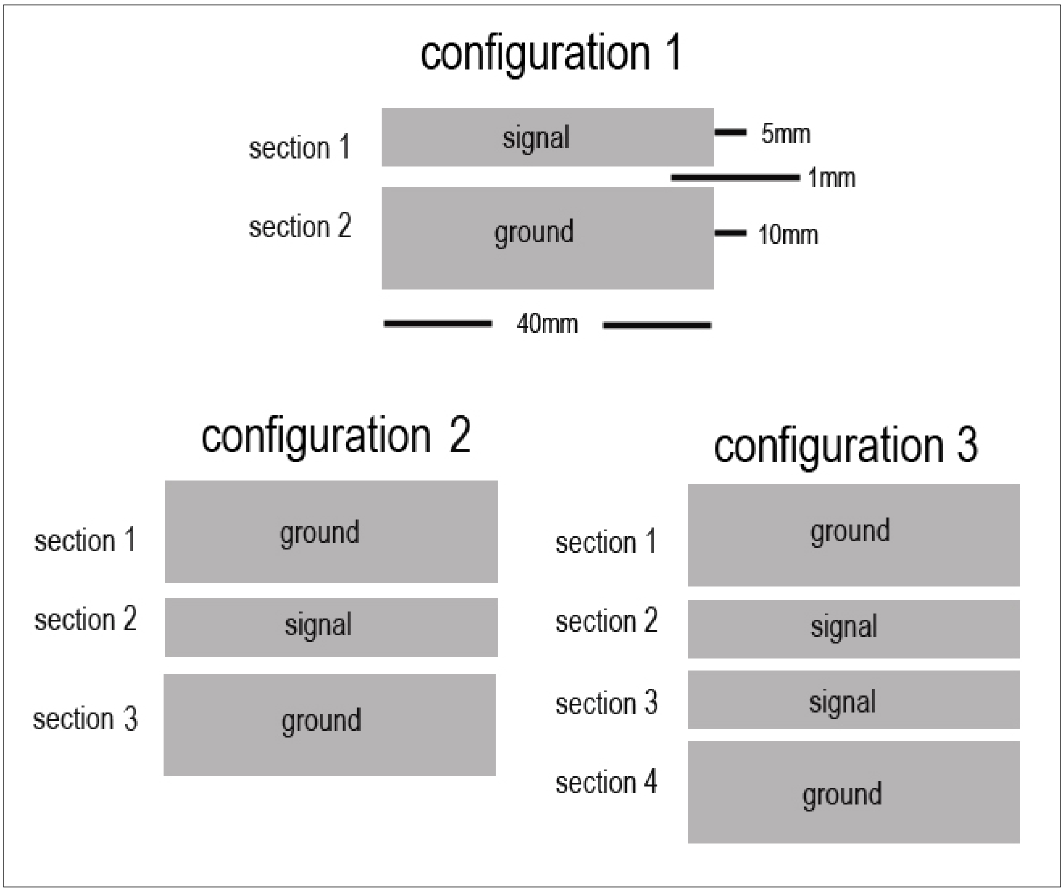
4.5 Prototype patches.

The yarns to be used were the 170, 280 and 350 denier X-Static.
For all 3 of the samples, each one was woven in all 3 deniers and all of the specific dimensions were identical. This was the above sizes being applied to each of the 3 samples (Fig 85).
The length of the lines being 40mm was deemed to be sufficient for both the small signal (DC/resistance) and frequency tests in order to give an accurate result.

The lines were woven using a plain weave structure (Fig 86). To get an accurate measurement to the proposed sizes was going to be difficult, due to a few contributing factors. The small scale of the lines required, the loom used, the denier of the yarn and how hard the yarn was knocked into place using the reed, could all cause the lines to have non-uniform distances between them. With this in mind there was a +/-0.25mm margin for error.

This is another example of the issues regarding conductive fabrics etc and creating what is essentially a hard object/item in a soft flexible medium whilst trying to retain electrical precision. Once the test patches were woven they were handed over to Thomas Hill who was to test them for their performance.

Fig 85 illustrations of the transmission lines to be produced showing configurations and required sizes, Authors own illustrations



Each of the samples that were woven had the same size of signal and ground sections and the same 1mm gap in between each section.

Fig 86 Photograph of woven transmission lines, configuration 1. Authors own photograph

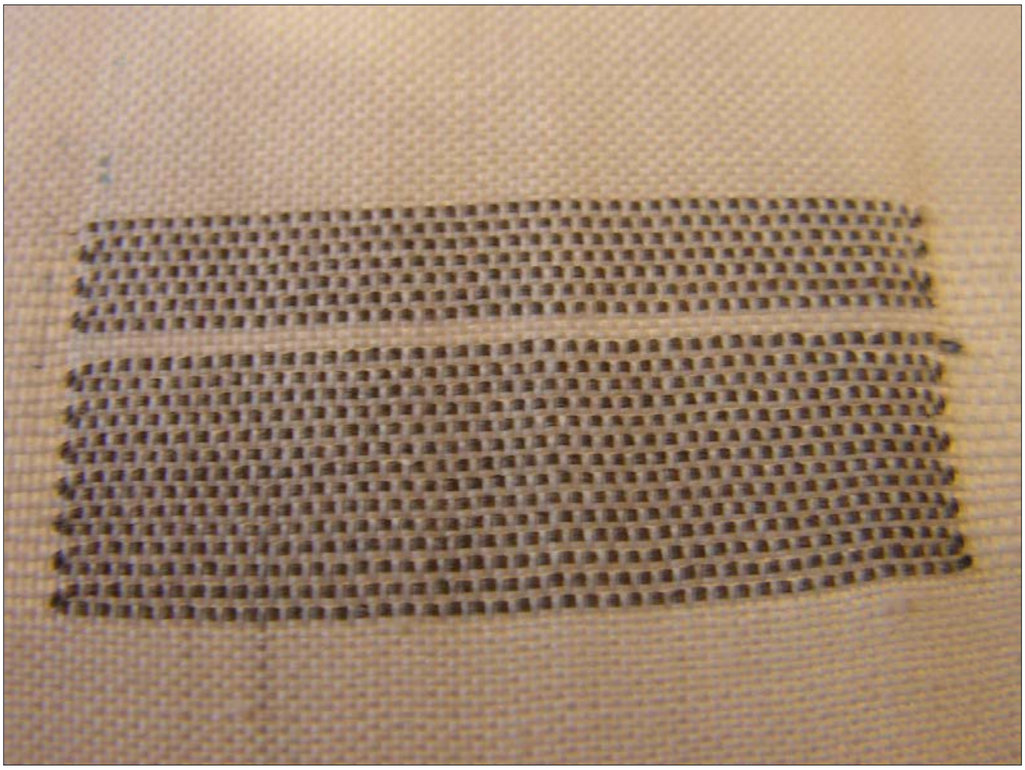


Fig 87 Photograph of woven transmission lines, configuration 2. Authors own photograph

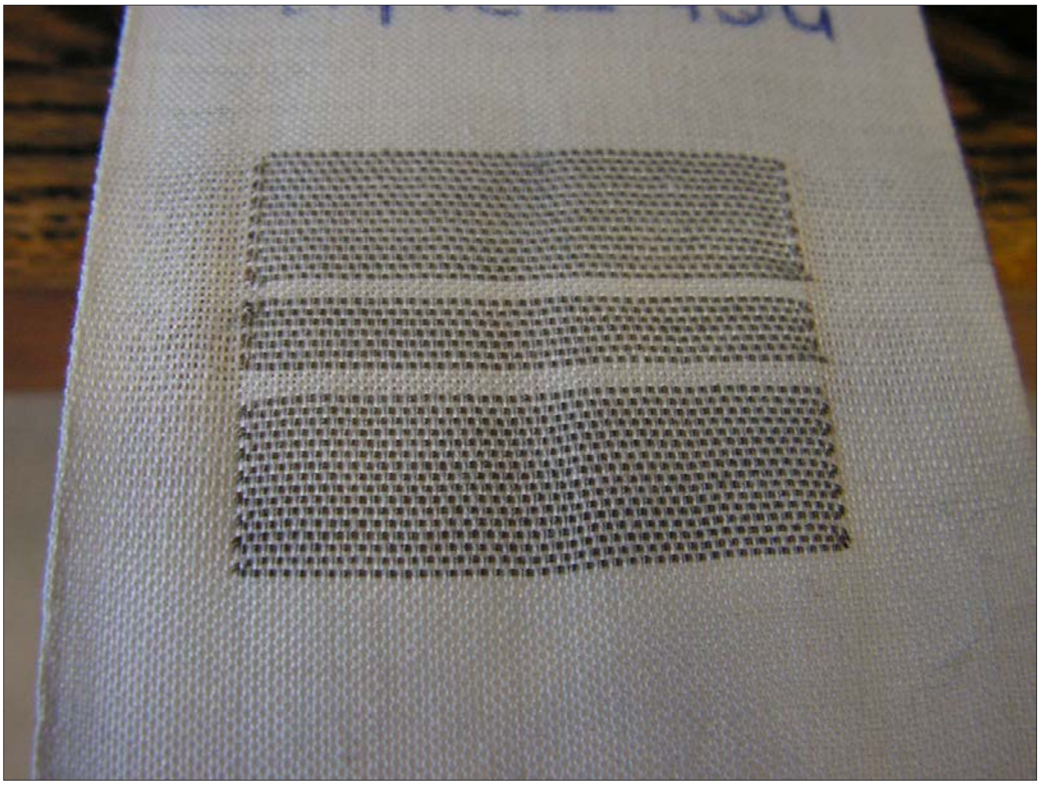
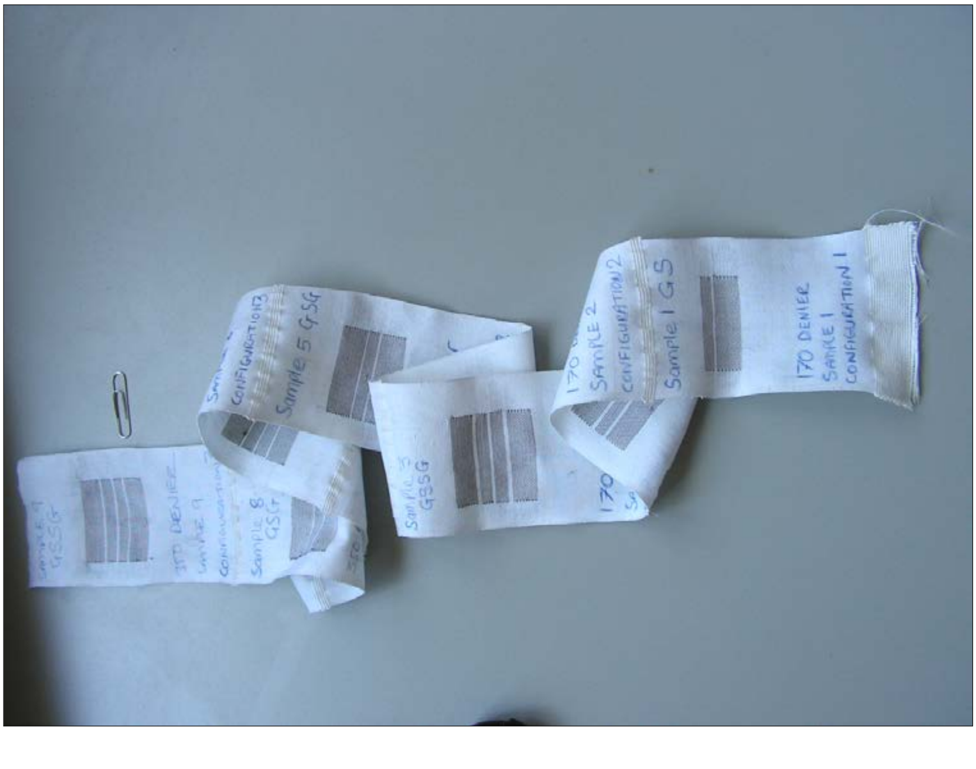


Fig 88 Photograph of woven transmission lines, configuration 3. Authors own photograph

Fig 89 Photograph showing all configurations of woven transmission lines. Authors own photograph



The following table shows the amount of picks in each of the samples using each of the available yarns.

	Configuration 1			Configuration 2			Configuration 3		
denier	170	280	350	170	280	350	170	280	350
Picks in Section 1	7	9	8	15	18	17	16	17	16
Picks in Section 2	14	16	16	7	8	8	8	9	9
Picks in Section 3	N/A	N/A	N/A	16	18	16	8	9	8
Picks in Section 4	N/A	N/A	N/A	N/A	N/A	N/A	15	16	15

The testing process for the lines is as follows.

4.6 DC signal testing of X-Static conductor tracks.

With having the lines woven in the 3 different deniers for each configuration, this would give a better and clearer indication of the electrical behaviour of the yarns.

Small signal testing was carried out using a high sensitivity multi-meter. When measuring the resistance of a conductor, a multi meter acts as a dc source delivering a small current through one probe and then attempts to pass it through the material to the other probe. By knowing the voltage applied and the current produced between the probes the multi meter is able to calculate the resistance of the material between the probes.

The connection of the probes to the line is via a pressure connection. This is how the multi meter operates. The probes are 2 metal rods coated in plastic insulation on the handles. This insulation means that there will be no disturbance of readings from any bodily contact. Would this though give an accurate reading every time?

If the rods were put in a slightly different position every time, there may be a slight discrepancy. There is however, no real alternative as soldering the connections would not work due to the probes being of a material that is not suitable for soldering. Along with this, the solder may react with the silver found in the X-Static.

The patches were placed on a non-conductive surface when tested to avoid any chance of a current path other than that of the signal line being used.

4.6.1 Test evaluation

The DC test (small signal) gave very erratic readings on the multi meter. This may well have been due to the pressure connection. As mentioned previously, how accurate the pressure connections were is unknown. Each reading was left for a few minutes until it had rested on a single value. The recorded resistances varied depending on where the probes were placed in relation to one another on the conductive track.

The lines were woven in the same manner as the antennas with the X-Static going only in one direction; this was in the weft and was only one single yarn the whole way along the line.

With this in mind, if the probes were placed at the bottom of each strip, one on the left and the other on the right, the signal would only have 40mm to travel to reach the other probe.

If the probes were placed at opposite ends, one top left the other bottom right; the signal would have further to travel. The exact distance depends upon the number of picks completed. As a simple solution, the distance would be roughly equal to the number of picks multiplied by 40mm. The further the signal has to travel, the greater the resistance experienced by the DC signal will be.

The probes had to be laid across the signal line being tested whilst ensuring that the probes are kept at the original points on the line in order to obtain the resistance of the whole line. Avoidance of the ground lines was also important otherwise alternative current paths would be encountered.

The average readings taken showed a correlation between the thickness of the conductive yarn and the resistance recorded. The heavier the yarn used, more or less meant that the resistance fell.

The results that were being obtained would be helpful to the Author as this side project works in conjunction with the research area that the Author is investigating. An antenna needs these transmission lines.

The tests though were not conclusive. This may have been due to an unreliable pressure connection between the test equipment and the textile sample. An alternative method of measuring was used.

4.7 Re-testing with a 4 wire DVM

The second testing was carried out using a 4 wire DVM, fig 90,[73] instead of the multi meter Fig 91.

Fig 90 Image of a 4 wire digital volt meter

This would hopefully ensure reliable results. The DVM is a far more complex piece of equipment than the multi meter. It works by using 4 wires/probes as opposed to the 2-wire

[73] Commonly known as a Digital Volt Meter

configuration used by the multi meter. 2 live probes go to one end of the test strip and the negative probes go to the opposite end. One set of the probes work out the total resistance, whilst the other set calculates the internal resistance of the machine, cables and probes. It then subtracts it from the total resistance. This would in turn give the true resistance of the test piece only.

Fig 91 Image of a standard multi meter

The DVM gave consistent results, which was never offered by the multi meter. Using the DVM allowed the transmission lines to display very low resistive characteristics indicating the lines have low loss. Overall, the test strips proved at this point to be quite successful.

Along with the signal testing, frequency testing was also carried out.

4.8 Frequency Testing

Following on from the signal measurements, the X-Static underwent frequency testing. A signal of particular frequency is applied to the signal line of a test patch and the output signal frequency is then analysed. The output is then compared with that of the input signal to give a measure of the loss in the line and how the lines characteristics affect propagated signals.

With the lines having small dimensions there is the chance that a significant amount of loss would be experienced because of the configuration of the signal track. In simple terms, loss is the power decrease caused by resistance in a circuit or circuit element. When frequency testing, the effect is that the output signal differs from that of the input. This is best measured with a digital oscilloscope[74].

As the X- static yarns again are placed alternately with the cotton, there is this separation between the conductivity. The theoretical effect of this is that an inductance or capacitance forms between the picks of conductive yarn. This results in a resistive force on the line.

This can contribute to a proportion of the lines loss characteristics.

4.8.1 Test Procedure

Frequency testing on transmission lines requires a signal source generator. This is used to produce a signal that is applied to the track. Along with this, an oscilloscope is used and this displays the electrical signals, both input and output. This allows the comparison to be visual. The digital oscilloscope also has the capability to give exact values of frequency and wavelength. This proved to be a far more accurate and reliable method of testing than that of the multi meter.

Probes again are used as a method of taking the reading. They measure the frequency from the generator to the test strip and then again from the test strip to the oscilloscope. The method allows only for the output signal. If a comparison is required between input and output, another cable is required and this must run from the input end probe directly to the 2nd channel of the oscilloscope, the bypass test strip. This will enable the scope to display both waveforms adjacent to one-another for comparative analysis.

The test results that followed brought to light an amount of loss present in the fabric lines that was not noticeable from the initial tests. The proportion of voltage loss increases with the frequency. Once the frequency gets into the MHz range the loss became significantly noticeable whereas in KHz no loss was apparent.

All of the transmission patches went through the same testing procedure and the results were almost identical despite the various deniers used and the line configurations.

[74] An electronic instrument used to observe and measure changing electrical signals

4.9 Conclusion

To summarise the test results, the CPW configurations for the transmission lines proved to be very successful and competent at a range of frequencies. The losses were relatively small when compared to what the predicted outcomes would be. The waveforms that were shown during the test procedure are smooth sinusoidal signals[75]. Cross talk was present; however this could be controlled to a certain extent.

At higher frequencies the transmission lines displayed a certain amount of loss characteristics. This increased with frequency when it was in the MHz region.

There was a notable amount of difference between the characteristics of the differing X-Static yarns which could have been down to the amount of conductivity within them.

It is encouraging to see that the 3 X-static yarns were again successful. The same 3 that were identified for use in constructing antennas have shown reliability when used in other aspects of this area. This would allow for the transmission lines and the antennas to be constructed from the same yarns, which in turn would help the aesthetics of the finished antenna, as there wouldn't be a combination of different yarns being used.

[75] a smooth succession of waves or curves

5 THE FINAL CONCLUSION

This document is written to enable audiences from both design and Electrical Engineering, to understand how this project was conceived and executed and enable the reader to understand how the practical experiments were carried out.

It was a challenging project of high order with an inter-disciplinary collaboration being paramount in taking the investigations forward. These investigations and experiments were carried out from October 2003 through to October 2006. Wearable textile antennas are a growth area but at the point of the research it was still in an embryonic state with very little information available due to the secrecy surrounding the research laboratories working on this subject.

At the beginning of this program of research, the term ‘electro-textiles’ was still relatively new. The specialist area of, textile antennas, was even more so in its infancy. Conducting a literature search would result in a few websites where information could be gained.

If the same search was to be done today, the outcome would be different. Smart textiles, electro textiles and plastic electronics are buzz words that when typed into a search engine, will result in page after page of websites discussing this particular topic and research and development companies informing us of their latest technical innovations. More academic papers are available in journals and the area continues to grow.

It is obvious that there has been significant growth in the area and with this is the question, is the Authors work still current and viable or relevant?

This conclusion aims to look at what initial questions were set by the Author and have the outcomes been achieved and to what level? Along with this, the future of the Authors specialism will be addressed and to where it fits in within today’s research and development programs. Possible further research studies will be looked at in the final chapter.

5.1 The initial questions

The investigations were split into 3 strands. The questions that would be addressed were as follows;

Is it possible to produce good quality conductors in a range of fabrics?

Is it possible to construct reliable and useful transmission lines and antennas on fabric using these conductors?

What performance can be expected from such components?

The summary and findings of these questions will be looked at and individual conclusions noted.

5.1.1 Is it possible to produce good quality conductors in a range of fabrics?

One of the main objectives was that the fabric needed to retain its natural handle and drape and not act like a fabric that had integrated components.

This was the rationale for using weaving. To be a truly integrated antenna, it was to be woven into the cloth at the point of production.

The most contributing factor for this would be the correctly sourced yarn.

Initial experimentations were to investigate woven structures and source conductive yarns or yarns and wire in order to create a conductive yarn.

The structure would be important as any integrated part needed to be secure. This is in terms of the additional yarn which had to sit correctly within, and on, any cloth that was woven.

Experiments included the spinning of yarn, although very unorthodox methods were used, and these included using cotton and tinned copper wire.

There were too many issues involving the use of wire. There wasn't enough flexibility, when flexed it remained in this state. Also the problem of stress fractures occurring due to the flexing. This results in loss of conductivity due to the breakages.

Air mingling methods with yarn were also investigated and tested. These too were unsuccessful. The wire was never covered adequately and the problem of the wire breaking was also prevalent.

At the start of the research project, conductive yarns were not very common. To obtain any small amount from producers to carry out the investigations was very challenging.

One yarn that was obtained was X-Static. This yarn contained silver and had all of the natural characteristics of a standard yarn. It was possible to obtain small quantities of a 30 denier and 70 denier, these yarns were then spun together in order to create a heavier denier.

Although a yarn that had natural characteristics had been sourced, there was still a question mark over its conductivity levels.

Initial woven structure experiments were carried out on an 8 shaft table loom. The warp consisted of 3 different yarns, cotton, polyester and Tencel. The plain weave structure was concluded to be the most successful in order to facilitate an antenna. This was due to the more concentrated area of conductivity being achieved as the conductive yarn only had to pass over and under 1 warp thread.

With having identified a suitable structure it was important to see how the yarns behaved when woven. Initially a larger sample area, but narrow in width, was constructed entirely of the conductive yarn. This was done in order to ascertain its properties. Does it retain a natural drape etc? With positive outcomes from the X-Static, single track conductors and conductor loop samples were woven in order to test for its conductivity.

The results were positive in the X-Static performing as a conductor, and in turn, were used to sample the woven antenna.

A reliable conductor was achieved but this wasn't sampled in a range of fabrics. Only one fabric sample was woven.

With developments taking place with conductive yarns becoming more common place, it is fair to say that X-Static may not be the best yarn to use. At the time of the initial experiments though, it proved to be the most successful.

5.1.2 Is it possible to construct reliable and useful transmission lines and antennas on fabric using these conductors?

To take something which is generally of a rigid construction and replicate it using a soft, flexible substrate is a challenging prospect. Within electro/smart textiles, that is a major hurdle to overcome.

This is evident when it comes to antennas and transmission lines. Can these components be constructed and integrated with a textile, and still function?

The conductive yarn had shown enough positive qualities with its conductivity and its ability to 'act' like a standard yarn. How would it be when used to create antenna samples and transmission line samples?

It wouldn't be sufficient just to concentrate on the production of an antenna as it requires other components to operate. One of these is a transferral of power. It needs something to carry a current from a power source which is what a transmission line does. This also requires being of a textile nature.

The transmission lines were produced using the same X-Static yarn as was used for the construction of the antennas, and in the same deniers, 70, 280 and 350. This was carried out in collaboration with another researcher Thomas Hill who was to undertake all of the testing in the dept. of Electrical Engineering.

3 configurations were considered and then woven and tested for their suitability to carry power. After various test methods were carried out, the outcome was positive. The X-static had proved to be a reliable and useful conductor for the transmission lines.

With the construction of the antennas, initial experiments were to weave a folded dipole antenna. This was going to problematic due to the shape of it and integrating successfully as an additional weft would be difficult.

To have more chance of the antenna working, it would be beneficial to have a surface area which had a heavy concentrated area of conductivity. The first samples were woven with the X-Static being used in every pick in order to achieve maximum conductivity. This however gave rise to issues of the yarn sitting raised off of the face of the fabric and the surrounding area being buckled. Aesthetically the antenna wasn't acceptable. It was difficult to weave and whatever was produced manually had to be produced on an industrial loom also so design and ease of weaving was important.

Another antenna design was supplied for a dipole antenna. This was woven with the conductive yarn being introduced on every other pick. This allowed the yarn to sit better within the cloth but was the amount of conductivity being compromised? Testing alone would identify this.

Again, aesthetically the antenna didn't look uniform. The weaving process again for this may have been difficult for industrial machines to reproduce.

A final design was developed in collaboration with the dept of Electrical Engineering for the Author to sample. The patch antenna was an easier shape to reproduce and could be done so quite accurately. This is an important factor that the size of the antenna can be crucial when it comes to measuring the performance.

This was again woven with the X-Static yarn being introduced as an additional weft and being used in every other pick.

Aesthetically the antenna was pleasing. The shape was easier to reproduce by the weaving process and more importantly, it was replicated by Cash's of Coventry on the industrial jacquard loom.

The antenna was woven in all 3 deniers in order to be tested.

Both the transmission lines and antennas were successfully integrated. It is important to note that they are only samples and much work would be needed in order to achieve a totally integrated and functioning textile antenna.

5.1.3 What performance can be expected from such components?

As mentioned previously, the transmission lines displayed a certain amount of success in terms of performance.

The antennas would be tested to ascertain whether they had the ability to resonate, and if so, how efficient were they?

The dipole and the folded dipole antennas were tested using the waveguide analyser. Due to inconsistencies with the weaving of the antennas, it was difficult to gauge whether the measurement that was given was to be reliable. Along with this was the problem of connecting the Balun from the analyser to the antenna sample. This would also have some bearing on the outcome of the results as an insufficient connection would inhibit any flow of power into the antenna sample. It was concluded that the dipole and folded dipole would not be suitable for use as a textile antenna. This was mainly down to the difficult process of weaving it successfully into cloth. However, some of the results do indicate that there was something happening with regards to the samples resonating to some degree, although it wasn't within any acceptable parameters.

The patch antenna that was produced was successfully woven with a manually operated loom and also with an industrial jacquard loom,

Initially it was hoped that the industrially produced antenna sample would give a better result than the manually produced one. This was due to the way in which it was woven which gave a larger conductive surface area and also it was anticipated that the yarns would be tighter and closer together giving rise to a stronger conductor.

The initial patch antenna samples gave mixed results. Some samples indicated that there was a certain amount of resonating occurring when compared to a standard copper patch antenna.

One thing can be concluded from this. The idea of a totally integrated textile antenna has been demonstrated and is sound. It will need significantly more research and development to make it commercially viable.

5.2 Future research

Future investigations for the Author could include the use of CAD embroidery to develop textile antennas and also the use of flexible conductive inks.

CAD embroidery would enable an antenna to be constructed with a very compact and concentrated area of conductivity. There is also the possibility that an antenna could be incorporated into an embroidered design which along with the functional aspect gives a fashionable aspect to it.

The rise of printable conductive inks can also allow for further investigations into digital printing with a conductive polymer and this again would allow for the antenna to be incorporated into a design on the fabric.

From the literature search it is evident that a lack of design results in the antenna being an additional component added to a garment. Consideration of design and how an antenna could fit within a design would start to make it fashionable as well as functional. At present this seems to be overlooked.

6 CONTRIBUTION TO KNOWLEDGE

Over recent years there has been significant interest and growth in the area of textile antennas. This document highlights some of the institutes that are working within the area and the outcomes that they have achieved. The Patria project for example has shown an integrated textile antenna that has good properties and works as an efficient antenna. Do these developments indicate that the work of the Author is no longer current? No it doesn't.

With all of the examples of wearable antennas that have been used throughout this document there is one underlying factor that links them all together. Each antenna has been a separate component that has then been attached to the garment and for the most part, the garments used have been outer garments. This in turn means that a wearable antenna is a seasonal thing. During the warm summer months a jacket is often not needed. Can this antenna be applied to a shirt for example?

The work of the Author was to challenge the findings of other research laboratories. The intention was to prove that a textile could fully facilitate a textile antenna and that the antenna was not a separate 'add on' component. With this, he intended the antenna to be integrated into various garments.

This still remains a possibility.

Through the samples that were produced, the patch antenna proved to be the most successful. This was an easier antenna to reproduce through weaving, but is weaving the best option to develop the project? The Author feels that the best way to develop this project is to explore the use of embroidery machines to embroider the antenna instead of the use of jacquard weaving. This could speed up the production as the threading of a loom is a very time consuming job.

It would also allow for a heavy concentrated conductive area.

Would the Author use the same X-Static yarn? No. The Author is aware that there are developments with conductive yarn and would source alternative yarns to test.

There is still much work needed in order to develop a fully integrated antenna into a textile but as yet, no evidence has been found to prove that this has already been done.

With the emphasis being on a design approach and not technical, the Author gave importance to the antenna being a totally integrated component and not an additional one worn against the body or attached to an exisiting garment.

This research does identify that a textile antenna can be fully integrated into a textile substrate. Test results show that the woven antenna responds and resonates to an extent but the Author acknowledges that further work is needed.

7 ANNEXE

7.1 Smart textiles, the future

Smart textiles or electro textiles; is there a correct title that describes this complex area? Either way it is evident that this is a growth industry. This can be seen in the amount of Universities and research institutes that are investigating some aspect of the area. With more recent developments with plastic electronics, the UK government are investing a significant amount of money proving even further, that they believe this to be a huge growth area.

How is market growth and is there consumer demand within smart textiles?
Has there been an increase in the last few years or is it still a struggling area with potential consumers? One reason for poor growth was highlighted by P Gough of Philips. He stated that there were not enough soft, flexible components to use in the production of smart textiles. Has this been addressed? It would seem that some components are now being produced in a soft, flexible state.

The research has identified that while it may have been functional, any garments produced were not fashionable. Being from a fashion print/design this was of importance. Has there been a closer link forged between fashion and functionality?

7.1.1 Fashion v Technology

Previously we have seen collaboration between sportswear manufacturers and electrical manufactures to develop items of clothing that have an electronic function. The Burton snowboard jacket with integrated MP3 and control panel situated on the sleeve and the Nike running shoes that communicated with the wearers Apple Ipod nano are just two examples that have received press coverage. This is a developing trend as sportswear manufacturers Adidas have produced a running vest with integrated sensors and following on from Burton, European outdoor brand Oxbow released a Bluetooth snowboard jacket for the A/W 2009/10 collection. This jacket allowed for mobile phone calls to be taken and also listening to music.
Will this be filtered down to mainstream?
An article posted on 'plus plastic electronics' website in March 2010 looked at this. The article titled 'Smart textiles: do they have mainstream appeal?[76]' interviewed 4 designers and smart

[76] Article can be found at http://www.plusplasticelectronics.com/SmartFabTextiles/Smart-textiles-do-they-have-mainstream-appeal-11693.aspx

textile developers to discuss there views. These were Angel Chang[77], Sandy Black[78], Despina Papadopoulos[79] and Kunigunde Cherenack[80].

It was apparent that there is still a huge amount to do with bringing smart textiles to the masses and giving it mainstream appeal. One concern was that there is still a detachment from the technical sector to fashion and that they didn't understand that garments would need to be totally washable and that different fabrics were to be used, Cashmere blend for example.

Another problem is something that was highlighted previously and that is the fact that fashion moves very quickly from season to season and the electronics industry has longer development cycles[81]. This will remain an ongoing problem.

These findings indicate that smart textiles are still struggling to achieve mainstream status and now as it was previously, the main application areas include aerospace, defence/military, automotive and healthcare.

7.1.2 Market growth

A report published in 2003 by Venture Development Corporation looked at smart textiles, the technology and where it could be implemented. They stated that the Smart fabrics and Interactive Textiles (SFIT) market totalled $300 million US dollars in 2003 with an estimated growth varying significantly by market segment over the following 10 years. They indicated that by 2008, the half way point, the overall market would be worth $720 million US dollars[82].

A report released in 2007 by BCC Research in the states gave the following figures for the US market only. In 2007 the US market was worth $79 million US dollars. The forecast for 2012 is that the market will rise to be worth $392 million US dollars[83].

In February 2011 a comprehensive global report on Smart fabrics and interactive textiles was released by Global Industry Analysts (GIA)[84].

They forecast that by the year 2015 the area would reach $1.8 Billion US dollars[85].

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77 A New York based fashion designer who creates smart textile fashion collections
78 Director of London College of Fashion's centre for Fashion Science
79 Designer and founder of Studio 5050. Her company is developing a set of standardised modules to make smart textile innovation easier for the fashion world
80 working on the TecInTex project, a Swiss initiative to make the basic technology for smart textile
81 Page 34 paragraph 3
82 http://www.prweb.com/releases/2004/05/prweb122626.htm
83 Report highlights can be found at http://www.bccresearch.com/report/AVM050B.html
84 http://www.marketresearch.com/Global-Industry-Analysts-v1039/
85 http://www.prweb.com/releases/smart_fabrics/interactive_textiles/prweb8117747.htm

The report states that the area is still in an embryonic stage but is poised for tremendous growth. This is in spite of reported slow adoption rates in several markets.

Along with this the recession has been blamed as textile demand has taken a blow worldwide.

It is stated that the area of technical textiles is set for a rapid return due to it extending far beyond the textile industry.

There is a huge leap in forecasted figures from that of $392 million US dollars in 2012 to the $1.8 billion US dollars forecast for 2015.

It is unclear if that projected forecast will reach that figure but what it does indicate is that the area of technical and smart fabrics is still a huge growth area and one that still has huge potential in terms of exploring new ideas and technologies.

7.1.3 Flexible components

With the increase in investigations into the development and application of plastic electronics, the problem of not having enough flexible components may be eradicated.

There was always the initial problem with smart textiles that most components used in electronics were rigid. To reproduce them in a soft flexible substrate was problematic.

With the introduction of plastic electronics, this may speed up the development of integral parts and allow for smart textile applications to be manufactured quicker.

7.1.3.1 Flexible Batteries

Supplying the antenna with power is paramount for it to operate. Batteries have always been seen as rigid and sometimes too large to be housed within a wearable garment that uses integrated technology.

Recent developments within battery technology have seen them become flexible and almost paper like.[86]

Japanese scientists developed the polymer based rechargeable battery which consists of a redox-active[87] organic polymer film which is around 200 nanometres[88] thick, Fig 92. Attached to this are nitroxide radical groups which act as charge carriers.

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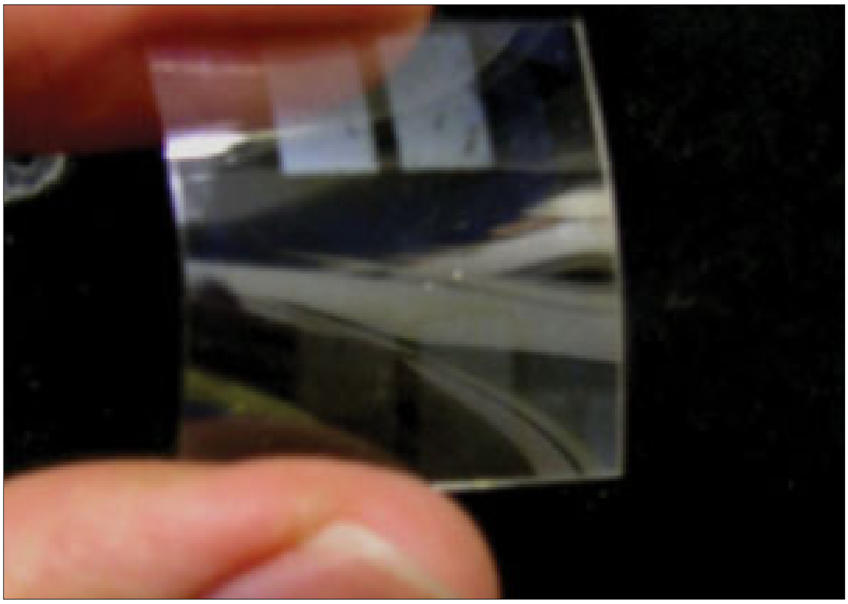
[86] http://www.rsc.org/AboutUs/News/PressReleases/2007/flexiblebatterypower.asp
[87] http://www.chemguide.co.uk/inorganic/redox/definitions.html
[88] http://www.edinformatics.com/nanotechnology/nanometer.htm

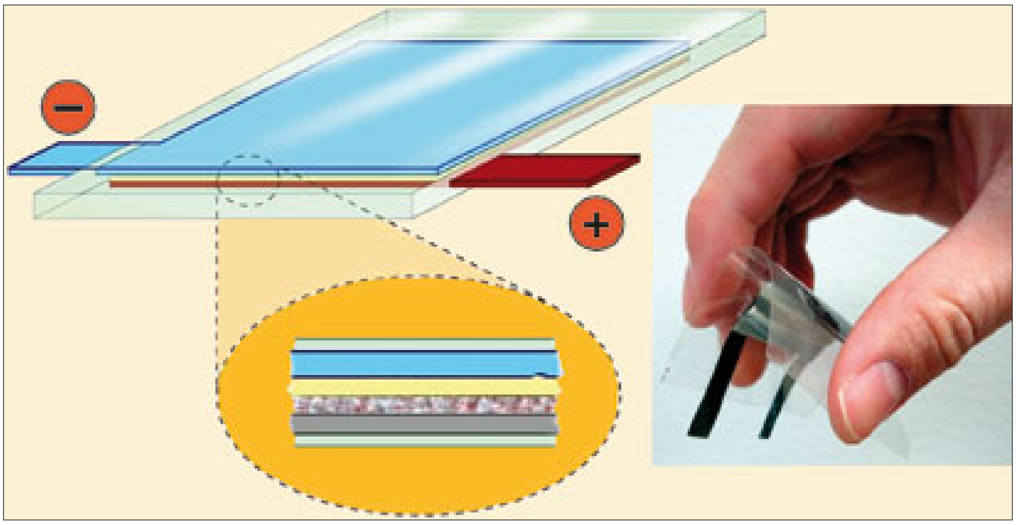
Fig 92 Image of a flexible battery [88]



Along with scientists from Japan, Scientists from the US have also designed an ultra thin flexible battery (fig 93).[89]

It is reported to have the highest charge capacity for thin film cells.

Fig 93 Image of a flexible battery [89]



[89] http://www.rsc.org/chemistryworld/News/2011/April/07041101.asp

This flexible power supply has been used in the Proetex project which was discussed in a previous section. This information was seen in a presentation at the the third Nordic Smart Textiles Network Meeting.[90]

The presentation was titled ‘Smart textiles for monitoring professional rescuers and fire fighters (the Proetex Project)’

The availability of thin and flexible power supplies will ensure that there is no weight penalty with wearable garments which could have been an issue previously and it will allow for easier integration into a garment.

7.1.4 Summary

Regardless of any negatives that have been raised with Smart textiles, which are particularly minor, it is still a growth area that is increasingly gaining interest and more importantly, investment.

Will there be a shift in fashion and smart textiles appear on the high street? Possibly not any time soon but this area is still very much in its infancy so at some point it may begin to filter through in people’s imagination.

Is this important? Would the technology be used in a sophisticated application or would it appear to be nothing more than a gimmick?

If the technology can be continued to be developed to increase the safety of search and rescue personnel and monitor vital life signs of the sick and infirm then it is a huge positive and an obvious application .

The development of plastic electronics could revolutionise the area and increase the varying applications where technology can be applied. It could also speed up the manufacturing process of smart textiles.

[90] http://www.sintef.no/Projectweb/pHealth2009/Programme/Smart-textiles-network-meeting/

7.2 Conductive tracks for Medical monitoring applications

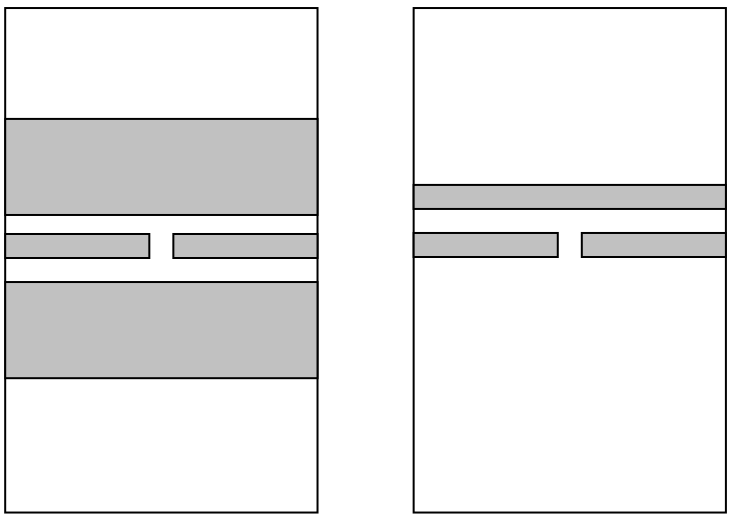
The samples were woven and also screen printed using a conductive polymer paste. They were manufactured as a result of the interest created by the previously constructed conductor tracks. Interest was expressed by Chinese researchers who were visiting Loughborough University department of Electrical Engineering, but were never met by the Author. Samples were produced that would undergo testing for their suitability to monitor a patients blood flow information.

The samples are the same size as previous, 6”x3”, with the addition of extra conductor tracks across the centre.

The conductive tracks were required in 2 sets. 1 set was constructed with 1mm track with a 1mm gap in the middle. Either side of the track was a 1mm space and above and below the centre track a 10mm conductor track was woven (Fig 94)

The second set also had a 1mm integrated conductor track with a 1mm gap in the middle. Above the track a solid 1mm track was woven with a 1mm space between the lower track with the gap (Fig 95).

Fig 94 and 95 Illustrations of conductor tracks to be produced, Authors own Illustrations



3 types of conductors were used. They were 2 x conductive yarns, and 1 x conductive paste.

The yarns that were used were BekitexBK50 and cotton with 0.05mm tinned copper wire, one commercially available and the other, non-commercial.

The last set of samples was printed with a conductive polymer paste. The paste is for use in the manufacture of rigid circuit boards and it was taken out of context and used on a flexible substrate.

The electronic jacquard machine was used to construct the woven samples and the conductive paste was printed using a silk screen, onto standard cotton. Both methods may have obstacles to overcome.

Attached to each side of the jacquard machine are knives that trim the selvage as the cloth is woven. This results in a continuous conductive loop being broken. This is not the case with the table loom as there is a continuous weft. To try and overcome this problem the cloth was woven using a 7 x 1 weft faced twill structure (Fig 96). This structure has the weft yarn crossing more warp yarns resulting in the weft yarn being exposed. It was hoped that with more weft yarns showing they would remain in constant contact ensuring stable conductivity.

The conductive paste is produced for use on rigid substrates, fabric is flexible. If the fabric is flexed too much the risk of the ink cracking is high. This would result in unstable conductivity. Despite this problem, in a previous research project carried out it was noted that the ink retains good conductivity when printed onto fabric. Within these previous tests a flexible conductive paste was used which was initially for use on neoprene diving suits. The fabric could be flexed and there were no signs of fatigue on the polymer paste.

The samples created for the medical application were done so using a standard conductive polymer paste. This was due to the flexible paste being unavailable at that point.

The samples were to be tested for their suitability to monitor blood-flow which in-turn gives the patients pulse rate. The initial tests are encouraging with the printed samples showing the more encouraging results. Fig 97 shows the original component that is used within a medical environment. Fig 98 shows the sample with the conductive paste printed onto it and Fig 99 giving an angled view of the same sample showing a clearer picture of the positioning of the wires internally and externally. Fig 100 is the sample woven with cotton and the integrated wire.

Fig 96 Illustration of 7x1 weft faced twill. Image taken from scotweave program

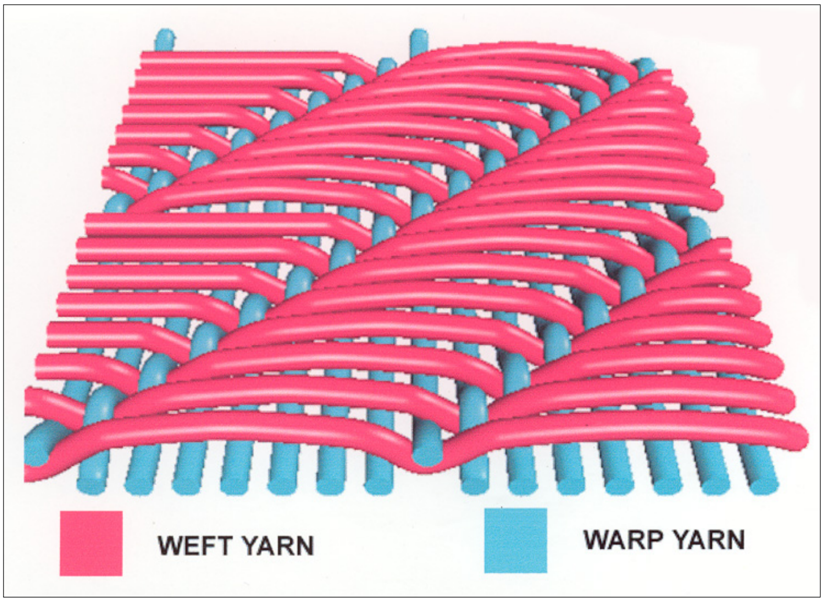


Fig 97 Image showing the original plastic part used in hospitals. Authors own photograph

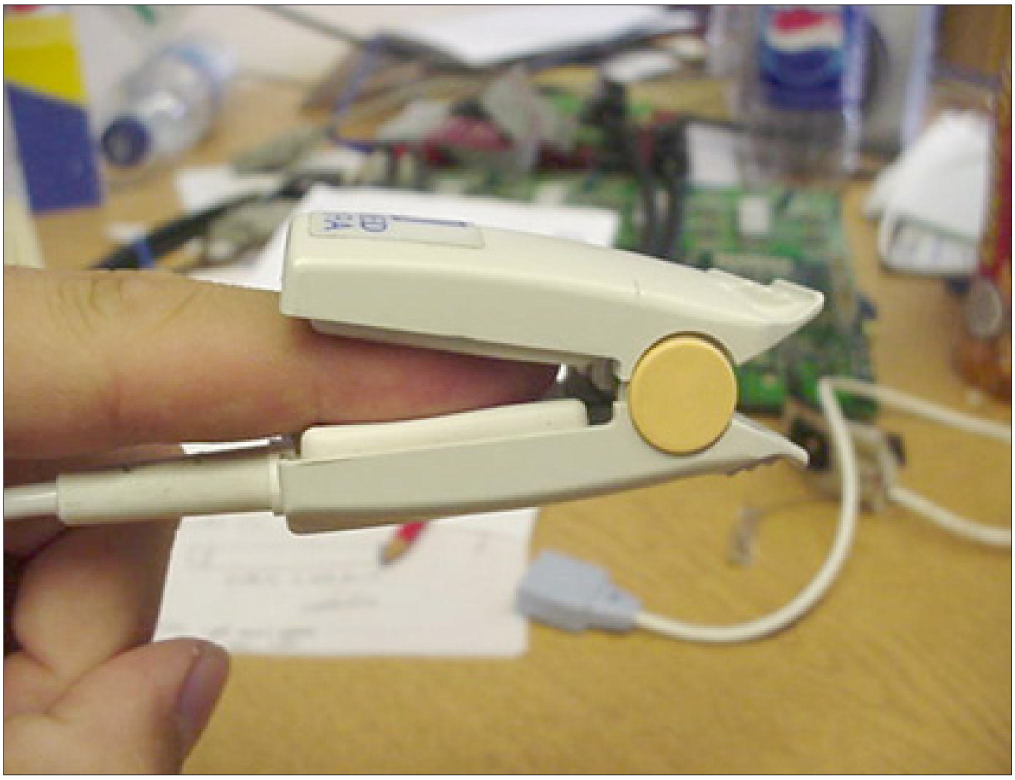


Fig 98 Textile sample printed using conductive polymer paste. Authors own photograph

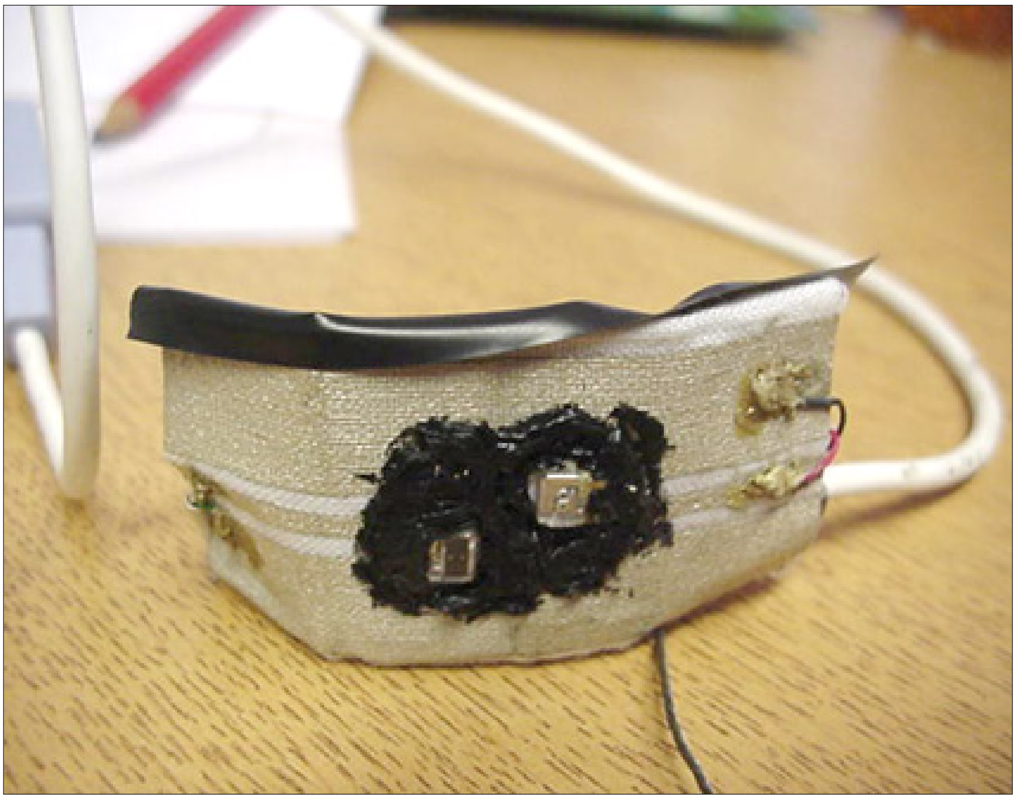


Fig 99 Image showing the internal section of the printed textile sample, Authors own photograph

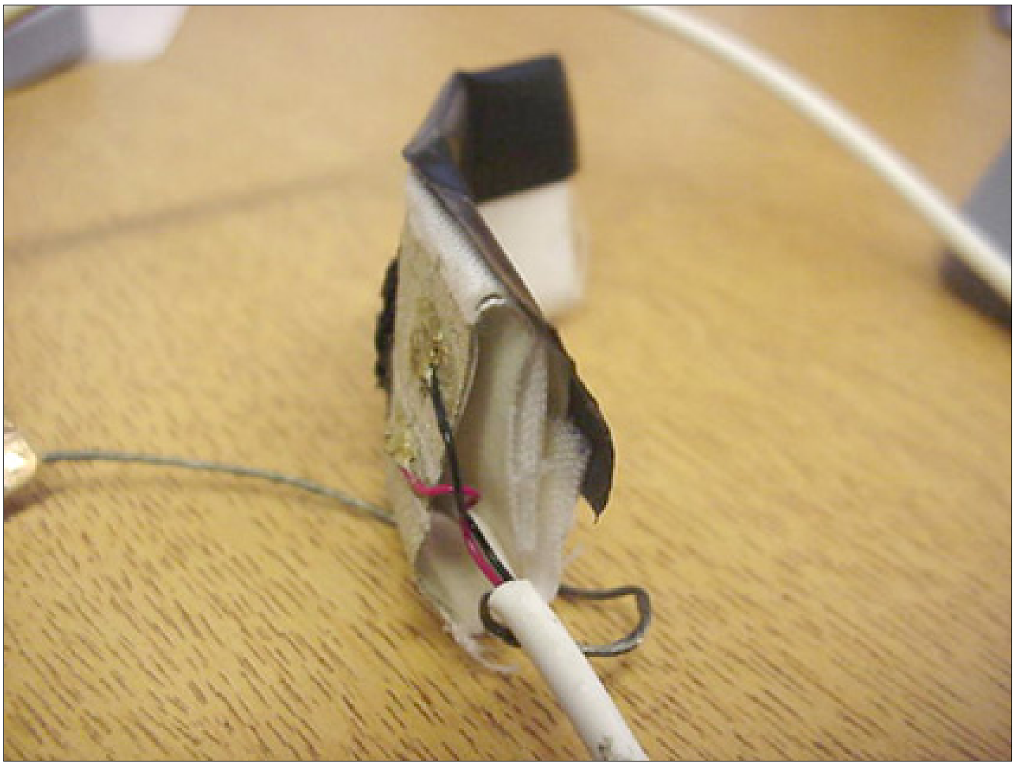
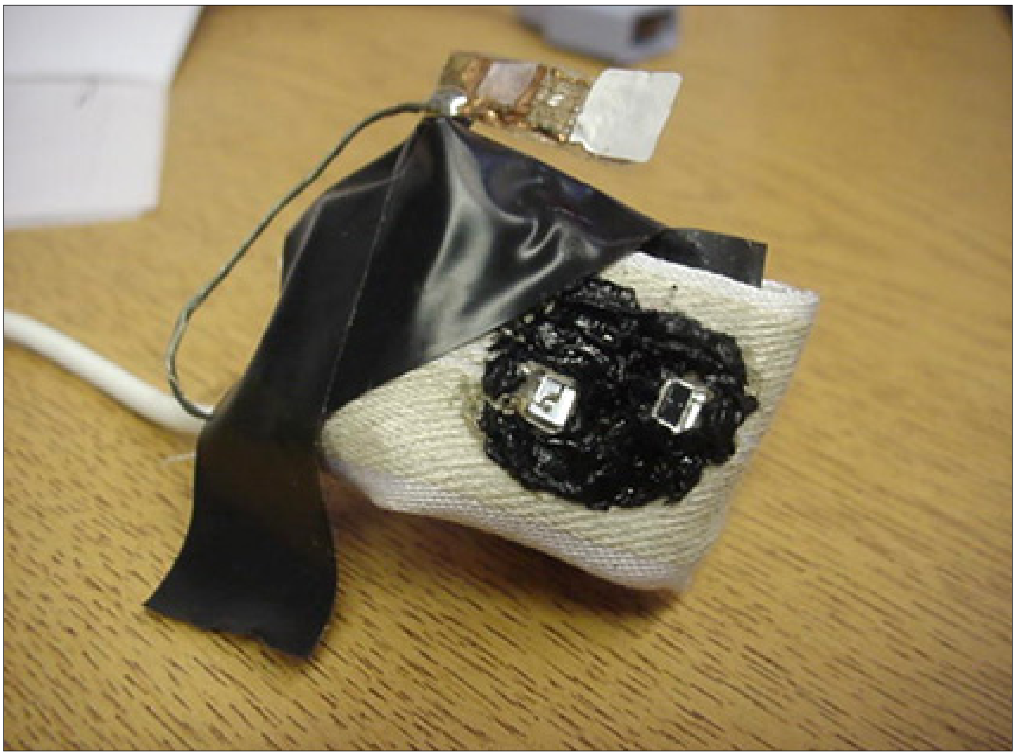


Fig 100 Textile sample woven with cotton and integrated wire, Authors own photograph



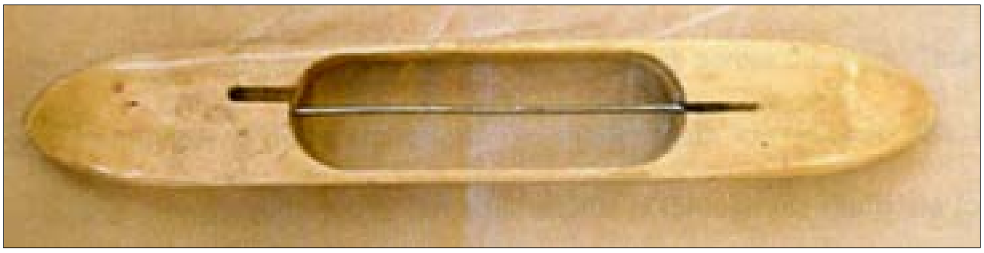
The primary aim of the samples was to ascertain whether a hard rigid object could be replaced with a soft fabric one. The idea being more comfort for the patient and also as it flexes with the finger it could give a more accurate reading.

7.3 WEAVING PROCESS

In order to produce a cloth 2 yarns are required. One called a warp yarn and the other is a weft yarn. The warp yarns are positioned on the loom in a flat vertical position and the weft yarn crosses the warp horizontally.

The weft is wound onto a bobbin which is then fitted into a shuttle (Fig 101) that carries the weft across the warp.

Fig 101 Photograph of a shuttle. Authors own image.



The 8-shaft table loom (Fig 102) used for the experiments is operated by hand. The threading plan uses consecutive warp ends threaded through the shafts beginning with shaft 1 and progressing in sequence through shaft 2, 3, 4, 5, 6, 7 and 8. This is known as a straight draft.

Fig 102 photograph of an 8 shaft table loom, Authors own image.

Operating levers on the left of the loom raise shafts 1, 3, 5 and 7 and 2, 4, 6 and 8 are on the right hand side. The numbered shafts operate the lifting of the warp threads to allow the weft to pass through. The majority of the samples that were produced were constructed using a plain weave structure. The plain weave is the simplest structure as it is 'under 1 end and over 1 end'. This is also the strongest of the weave structures as it has more thread intersections than any other.

To weave a plain weave structure all of the odd numbered shafts are lifted. The weft is then passed under the raised warp and over the warp threads that are located on the even numbered shafts.

The space between the raised and non-raised warp threads is known as a 'shed'. The weft is passed across, adjacent to the closed end of the warp and at right angles to it. When the weft is through the shed the odd number shafts are lowered resulting in the warp threads all lying flat. The reed (fig 103) is then brought forward to position the weft yarn.

Fig 103 Photograph of a reed. Authors own image.

The weft has to travel back across the warp. This time all of the even numbered shafts are raised. The shuttle again travels under the raised warp yarns and over the non-raised. Once the shuttle is through the shafts are lowered and again the reed is brought forward to position the 2nd weft tightly against the 1st. This process is continued, alternating between lifting the odd and the even shafts until the entire warp has been filled. The warp yarn is wound forwards periodically and the cloth is collected on the front beam.

Along with hand weaving, many of the samples were woven using the electronic jacquard machine (Fig 104).

Fig 104 Photograph of the electronic jacquard machine. Authors own image.

This was done in order to investigate the conductive yarns suitability for use with modern textile machinery. It is important for possible production that all conductive samples could be produced on an electronic loom.

7.4 UNDERSTANDING ANTENNAS AND HOW THEY WORK.

Delimitation within this research programme was the Author being from a print and textile design background and the need to understand the operating system of an antenna had never been considered to be important.

An amount of background information would be valuable in order to understand any dialogue between designer perspective and an Electrical Engineer.

One important factor to bear in mind is that the research is conducted from a design/textile approach and not the more scientific/technical approach generally used by Electrical Engineers. This is due to the information gained during this project being available to those working within the textile industry. The aim was to see if a fabric could facilitate a rigid conventional component used within mobile communications such as an antenna, but construct it using a soft material. This would allow for the expansion of the textile industry as this technology could be applied into various textile end uses. Health monitoring clothing for example that enables the body's vital sign to be monitored.

7.4.1 How Antennas Work.

To understand this area is very difficult. Most people have use of antennas every day in some form or another. This could be through watching television, listening to the radio or using a mobile phone. It could be said that we take it for granted that when we turn on the TV there is a picture or switch on the radio we hear music, and make a phone a call we get connected.

During this section common antenna terminology will be used, which will then be explained in the following sections.

It is intended that after reading these sections a greater but simpler understanding will be held by the audience which will in turn inform design decisions.

The basic purpose of an antenna is to carry information from one place to another.

An antenna is generally made from metal or a metallised substance. This is due to metal being an excellent conductor of energy/power. Radio and TV waves are generated typically by making electrons oscillate up and down on the antenna. Electrons are minute, lightweight and electrically charged particles.

The electrons generally oscillate when a variable voltage or alternating current is applied to the antenna.

Electrons are found in the outer shell of an atom. They are only held weakly and are therefore able to float from atom to atom under the influence of any electrical fields that may be present. The ones that have broken loose from the atoms and are called ‘free electrons’. It is these ‘free electrons’ in mass migration that give an electric current in a conductor. If the current is alternating, as in an antenna, the free electrons in a given locality move back and forth in unison.

When a negatively charged electron moves it leaves behind a positively charged hole. This is in fact not a hole but an atom with more positive protons than negative electrons. This movement is incredibly quick and the electrons show acceleration and deceleration. This is when the electron is coming to a stop and then starting up in the other direction. Generally this movement can be described as vibrating.

It is this movement of a large enough group of electrons in unison in one place that causes a signal in the transmitting aerial. This has a detectable effect on electrons in another place, which is the receiving aerial.

The process of this accelerating and deceleration of a charged body is then a source of electromagnetic radiation. This radiates out the sides of an antenna at the same frequency as the variable voltage that may be applied to it.

7.4.2 Magnetic and Electric fields

If an electron were still, in a resting position, the only field present would be a stationary electric field. For a simple explanation, imagine that an electron was a little round ball. Distributed uniformly over its surface would be an electrical charge. With no movement there is little happening. The electric field would point outwards from all directions on the electron. These field lines are the same for both the negative and positive charges.

This is called the ‘coulomb field’. This is always present regardless if the electron is moving or not. It is the coulomb field that plays a major part in the operation of antennas.

Once the electrons are in motion, two new fields appear.

Moving electrons will in-turn, produce a current. This is always surrounded by a magnetic field. To gain a simple understanding of how a magnetic field works and to see the electrons direction of movement, this simple exercise was discussed in a paper titled 'Why an antenna radiates' by Kenneth Macleish[91].

Point the thumb of the right hand outwards as if hitchhiking. The curled fingers represent the circular lines of the magnetic field around the electron. If the thumb is pointed in the opposite direction, the magnetic field reverses. A vibrating electron also gives rise to an alternating magnetic field.

Along with that, the second field is an electric field. This is a result of the electron's acceleration.

7.4.3 Vibration

To achieve a continuous signal using electricity, the electric current or voltage needs to change continuously. If a current were to continually increase, it would not be practical. The most effective method is to have the current increase for a short period of time and then decrease back to zero. This process would have to be repeated, increased and decreased, and that cycle would be repeated for as many times as is needed.

Another way a continuous signal can be achieved is by allowing a current to flow into a piece of wire or antenna for a short time and then stopping it and allow for it to flow back out again. This cycle would again be repeated for as long as was required.

7.4.4 Cycles

All aerials are electrical conductors of a finite size. They all vary in size but all remain finite in size. In turn, this means that any movement of electrons in one direction (electric current) will either fill or empty the conductor very quickly.

For a continuous signal to radiate, the power from the transmitter must alternately push electrons into the aerial then pull them out again. This continual pushing and pulling occurs for as long as the signal is needed. One cycle is one completed push and one completed pull.

7.4.5 Wavelength

This term is often used. A wavelength is radio waves that are composed of both an electrical field and magnetic field. As an example, if a current is passed through a length of wire it would

[91] http://www.qsl.net/g3yrc/antenna-radiates.htm

radiate a magnetic field and the polarisation of that field is in circles around the wire. With this there is also an electric field, which is polarised along the length of the wire.
The speed at which electricity and magnetism travels is just less than 300,000,000 metres per second. As an example, if an alternating current (AC) were sent through wire, after 1 second one wave would have travelled 300 million metres.
If the frequency of the AC current was 1 cycle per second then each complete cycle would have travelled 300 million metres.

7.4.6 Radiation Pattern

When the results of the antenna test are analysed, one result to be seen is that of the radiating pattern. What this is in simple terms is a visual representation of how an antenna distributes its signal. The visual is shown as an overhead view that clearly shows the pattern made. Examples of these can be seen in the Authors test results. The polar plot, a term for the pattern, shows this as a figure 8. This image shows that the antenna has gain. That means that the signals coming from the front and rear are stronger than signals coming in from the ends.

7.4.7 Polarization

As previously mentioned, a radio wave is made of 2 fields, one electric and the other magnetic. The two fields are perpendicular to each other and the result of this is an electro-magnetic field. Of the 2 fields, it is the electric field that is of interest. Wave polarization is determined by the antennas position and direction with the ground (earth’s surface).

The electric field is the same plane as the antennas element, element being the part of the antenna that is doing the radiating. This means that if the antenna is vertical then the polarization is vertical and vice versa.

What follows is a simple example of why polarization is important. If a receiving antenna is receiving a signal that doesn’t share the same polarization as itself, the signal could be reduced by almost 7 times. That is in comparison to a signal sharing the same polarization.
One thing that may happen with a signal is that it reflects off of objects and the field can actually change the polarization. If this happens, the result could be that a signal from a horizontally polarized antenna could come through loud and clear on a vertically polarized antenna.

There is however one polarization known as circular polarization. As the wave's travel they spin and in turn, it doesn't maintain a set polarization but covers every possible angle in-between. An advantage of this is that it reduces signal fade.

7.5 Summary

To completely understand the thorough workings of an antenna and microwave circuitry on a whole, it would be necessary to have studied the area of Electrical Engineering.

The previous sections illustrate the various elements that are involved in a signal being 'formed' and 'sent' and also highlight the complexity of the subject area.

The simplified explanations allow the viewer to gain a basic understanding of how an antenna works.

Collaborative projects allow for practitioners from various disciplines to come together and share their expertise. This sharing of knowledge illustrates that the need for complete understanding of other disciplines is not necessary. However, a basic understanding is important when communicating with other practitioners as it allows for quicker and easier design development.

The information given in the previous sections is very much the same for all antennas. How does this differ when it comes to working with Microwaves?

7.6 MICROWAVES

When discussing the use of microwaves with practitioners from different disciplines, a common mistake is to link the term microwave with that associated with microwave ovens. This is not the case. The microwaves used within the research topic do not induce heat in objects. They refer to the use of microwaves to communicate.

The microwaves in turn are a range of radio frequencies between about 1GHz (one gigahertz is around one billion oscillations per second) and around 300GHz. As a comparison, television transmissions normally occupy frequencies below the microwave region. This is from around 50 MHz to 600 MHz (one Megahertz is one million oscillations per second, 1 GHz is 1,000 MHz). Cellular phones operate in 2 bands, 800 to 900 MHz and 1.8 to 1.95 GHz. This again is just below the definition of microwave frequencies.

There is no formal definition of the frequency range for microwaves although it is stated in a paper by Thomas D. Williams[92] that many textbooks define all frequencies above 300 MHz as microwaves.

In this same paper he states that the term 'microwaves' seems to have appeared first in 1932. This was in a paper written by Italian Nello Carrara in the first issue of 'Alta Frequenza (high frequency). The term 'microwave' gained acceptance during the Second World War. It described wavelengths less than 30cm. The sizes of the waves were much shorter than those normally used for communication purposes at that time, but they were being used for RADAR.

A 30cm wavelength is equivalent to 1GHz.

Previously, radio waves and electromagnetic radiation have been looked at. What then is the advantage of using microwaves?

7.6.1 The use of microwaves

In the early part of the 20th Century, communications began using electromagnetic radiation. Most of the early practical systems used very long wavelengths (low frequency) which allowed the signal to travel very long distances.

The development of the 'valve' or the 'vacuum tube' allowed for controlled frequencies and modulation within electronics. This development led to the use of higher frequencies, more channels and the beginnings of commercial and industrial radio.

The 1930s and 40s bought various experiments and the discovery that higher frequencies could bring advantages to communications.

Within these experiments, it was discovered that microwaves were easier to control than longer wavelengths and that small antennas could direct radio waves very well. One of the main advantages of having such control is that the energy could be confined to a tight beam. This is generally known as a narrow bandwidth. The beam then has the advantage of focusing on an antenna many miles away which could make it difficult for interception of conversations etc. Another characteristic is that due to the high frequency, larger amounts of information could be sent. This is generally known as increased modulation bandwidth.

[92] Article can be found at http://www.wa1mba.org/micros.htm

The combination of a narrow bandwidth and the modulation bandwidth allow microwaves to be useful to RADAR[93] as well as communications.

These qualities led telephone companies to use microwaves. Antennas, receivers and transmitters could be placed at specified distances and these would relay the relative information.

7.7 Conclusion

The fabric antennas produced in this research could be used with low level satellites and the need to have this control of energy to reach the required destination is very important, hence the use of microwaves.

[93] Radar is an object detection system that uses electromagnetic waves to identify the range, altitude, direction, or speed of both moving and fixed objects

8 APPENDIX

8.1 FABRIC SAMPLES FOR LOW FREQUENCY TESTING

SAMPLE 1
WARP – 2/60s COTTON
WEFT – BEKITEX BK50
NUMBER OF PICKS – 4

SAMPLE 2
WARP – 2/60s COTTON
WEFT – 2/24s COTTON SPUN WITH 0.05mm TINNED COPPER WIRE
NUMBER OF PICKS – 3

SAMPLE 3
WARP – 2/60s COTTON
WEFT – 1x420 POLYPROPELENE SPUN WITH 1x30 DENIER X-STATIC®
NUMBER OF PICKS – 3

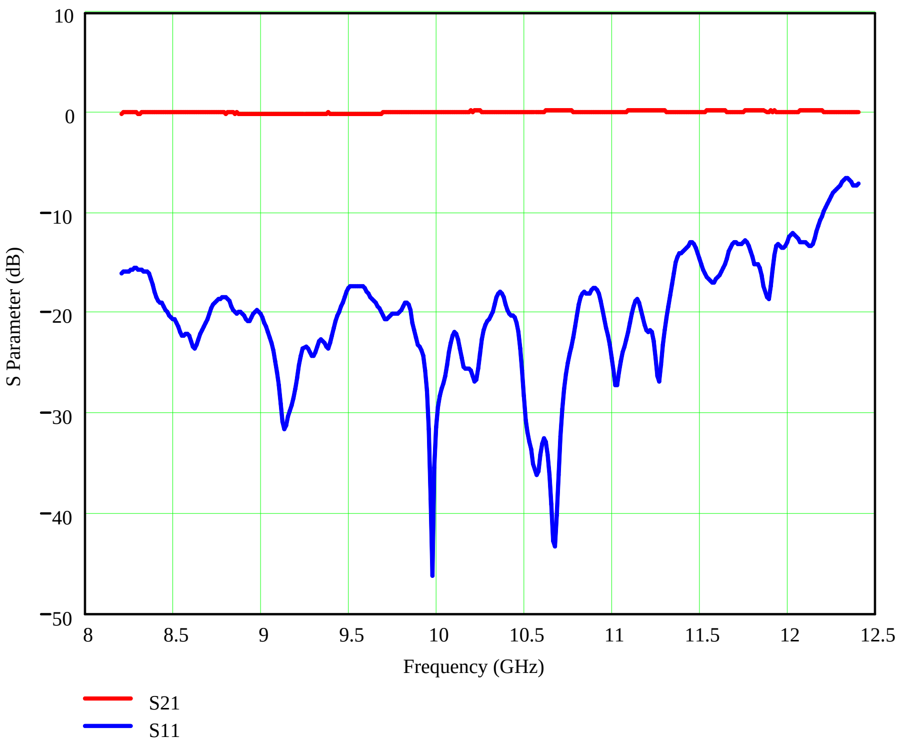
SAMPLE 4
WARP – 2/60s COTTON
WEFT – 30 DENIER X-STATIC®
NUMBER OF PICKS – 14

SAMPLE 5
WARP – 2/60s COTTON
WEFT – 1x100 GREY POLYPROPELENE 1x30/1 CCW/5% X-STATIC®
NUMBER OF PICKS – 4

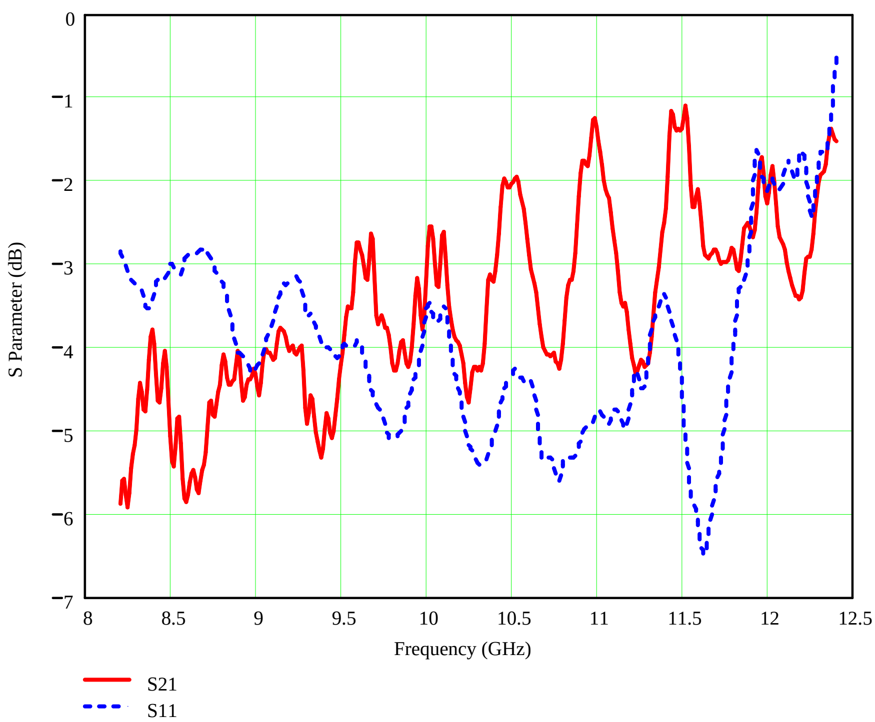
SAMPLE 6
WARP – 2/60s COTTON
WEFT – 2/24s COTTON SPUN WITH 0.10mm STAINLESS STEEL WIRE
NUMBER OF PICKS – 3

SAMPLE 7
WARP – 2/60s COTTON
WEFT – 70 DENIER X-STATIC®
NUMBER OF PICKS - 3

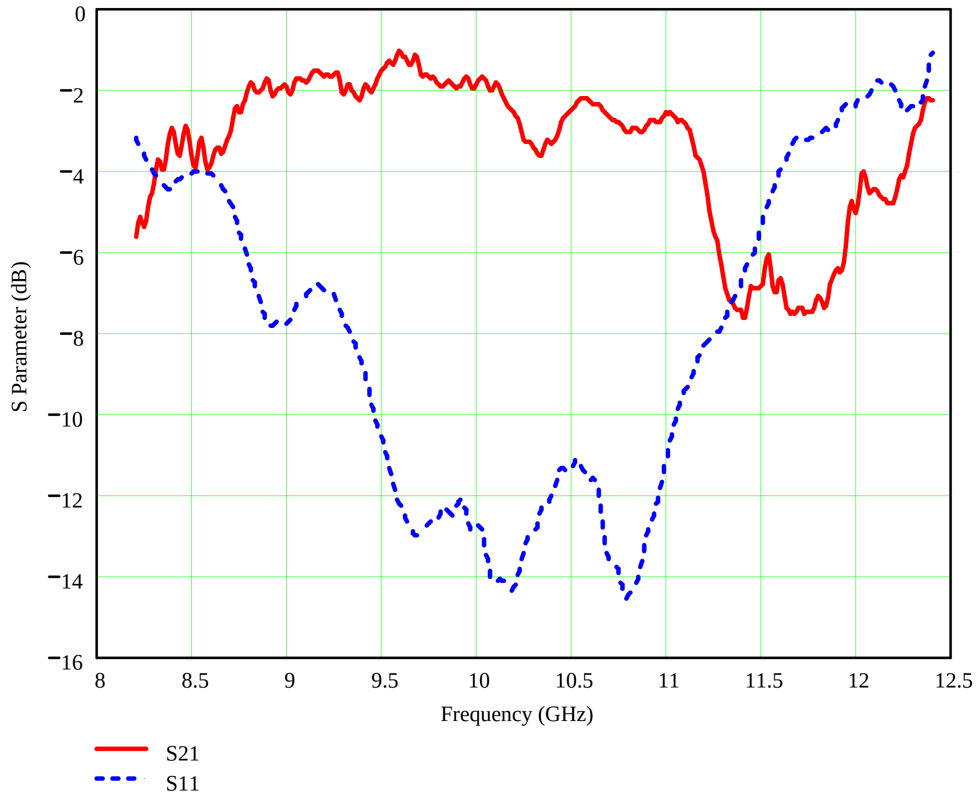
TEST RESULTS OF LOW FREQUENCY CONDUCTIVE TRACKS



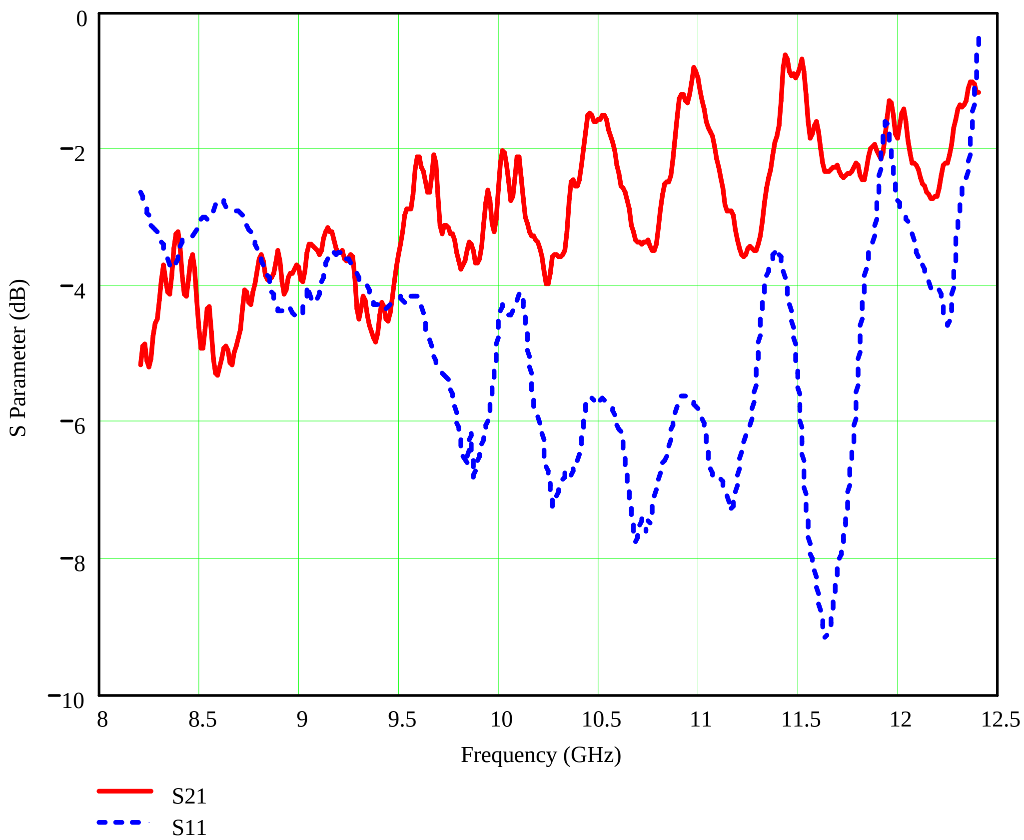
Material Alone



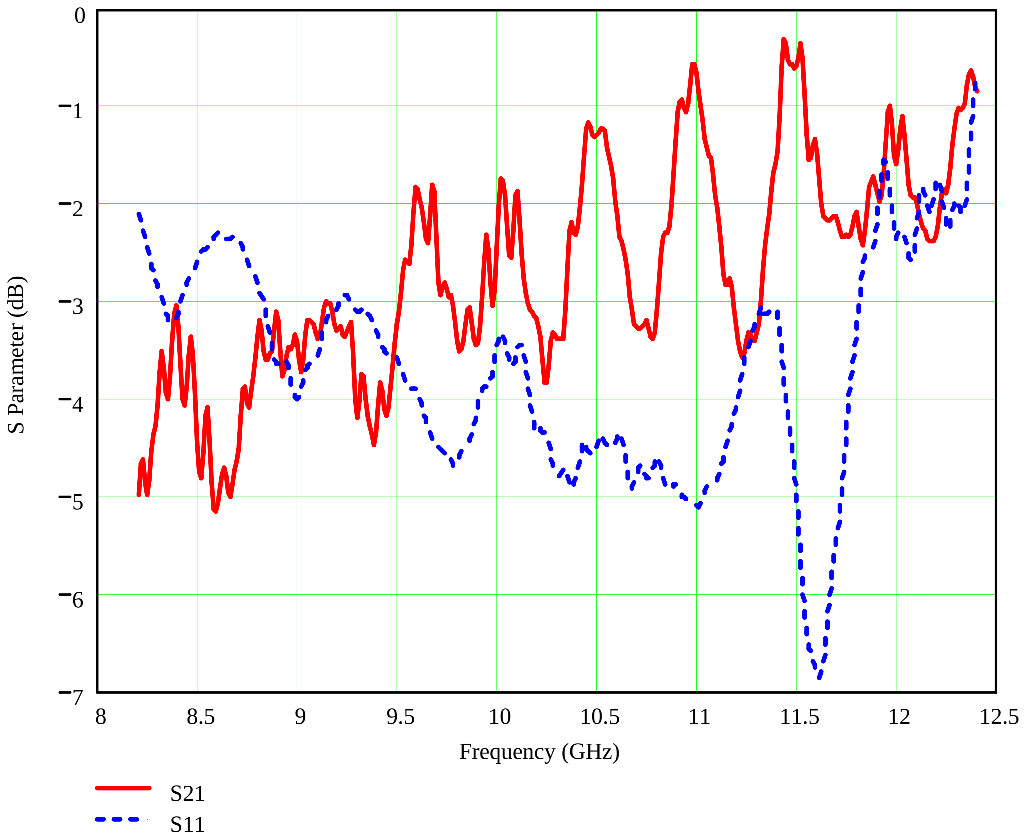
Sample 1



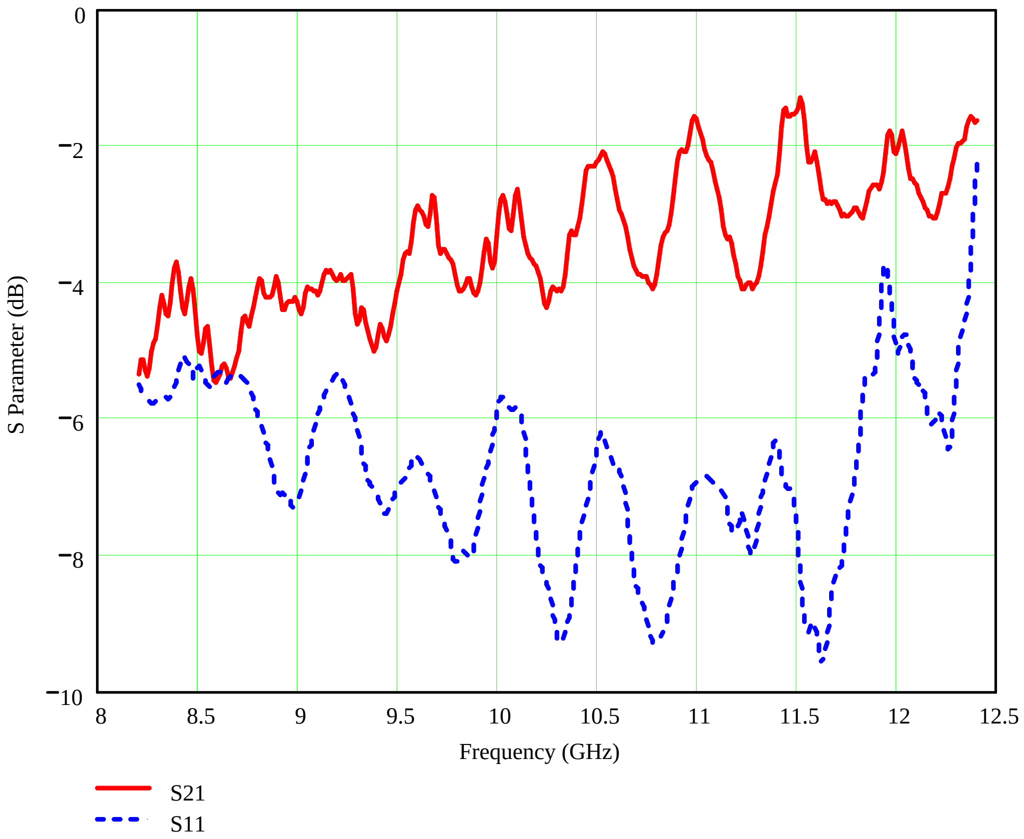
Sample 2



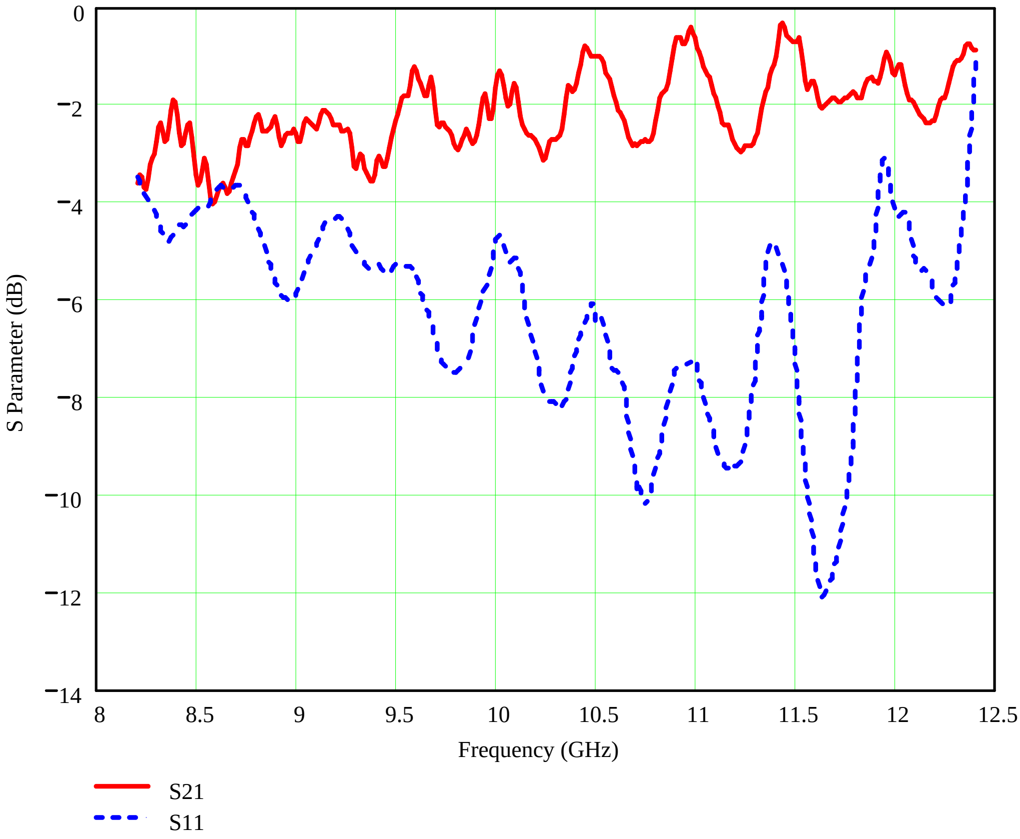
Sample 3



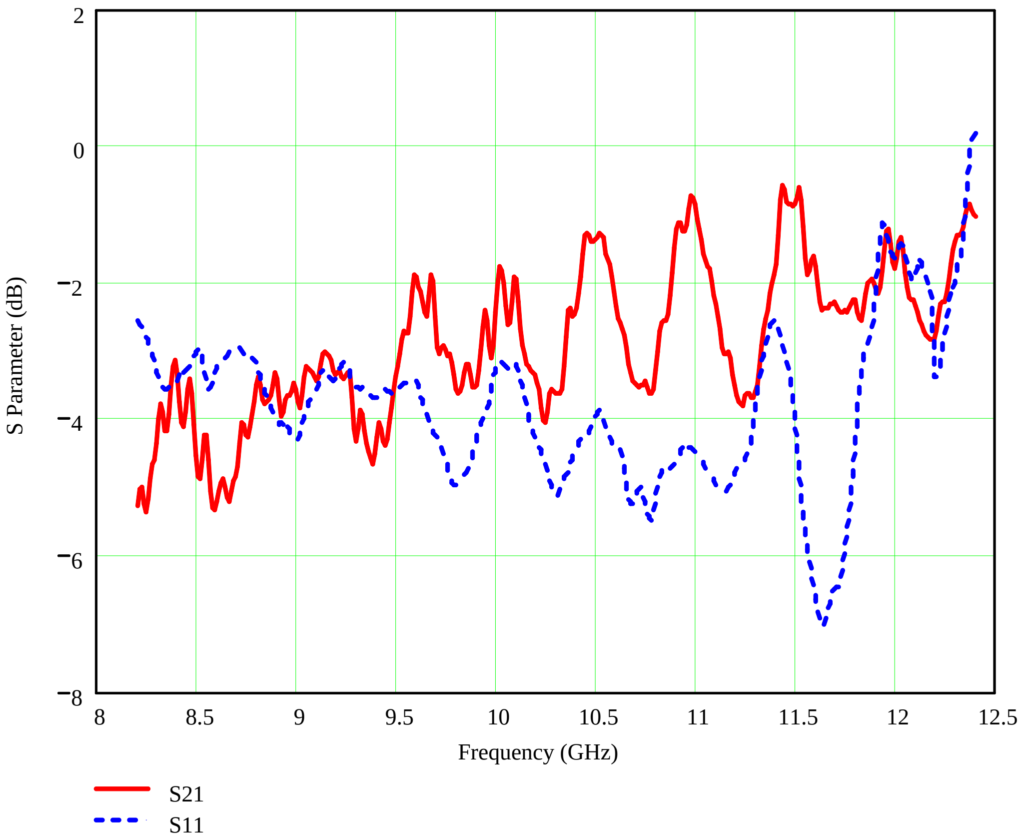
Sample 4



Sample 5



Sample 6



Sample 7

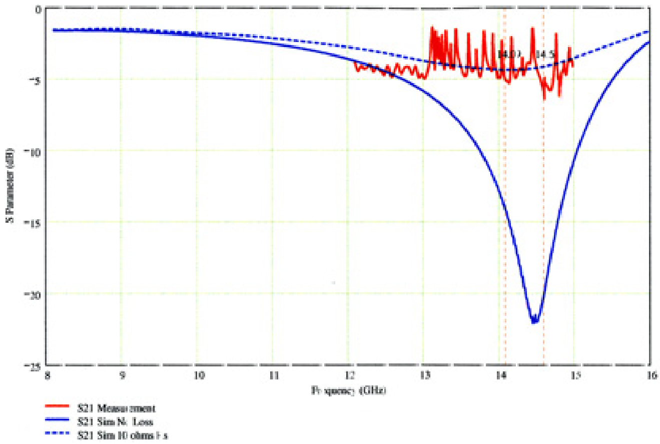
8.2 DETAILS OF YARNS USED IN METALISED TRACK TESTING

8.2.1 7MM LONG METALLISATION WOVEN INTO COTTON FABRICS

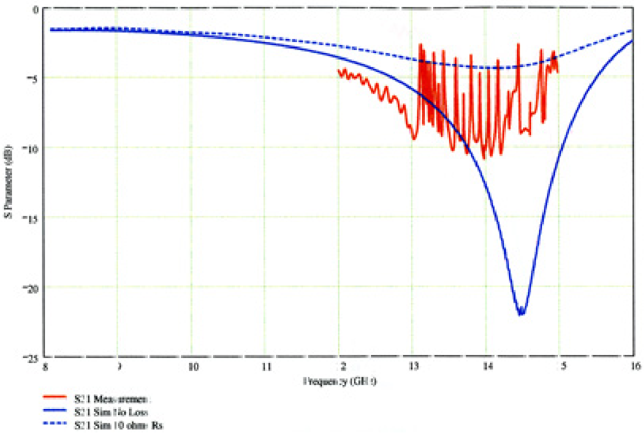
Samples were tested on <u>24th November 2004</u>

All samples are woven with a 2/40s cotton warp and weft.

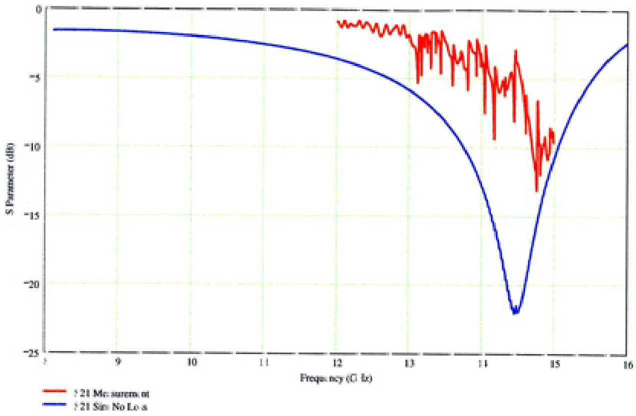
Sample 1 – Bekitex BK50. 4 picks



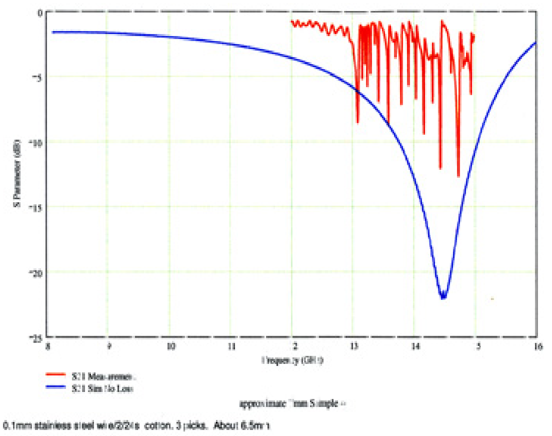
Sample 2 – X-Static, 70 d tex. 10 picks



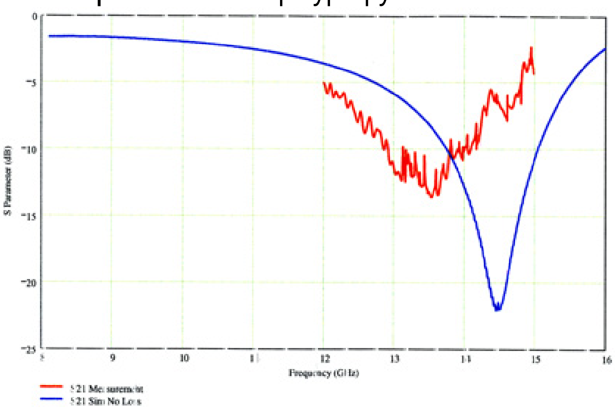
Sample 3 – 0.05mm tinned copper wire/ 2/24s cotton. 3 picks



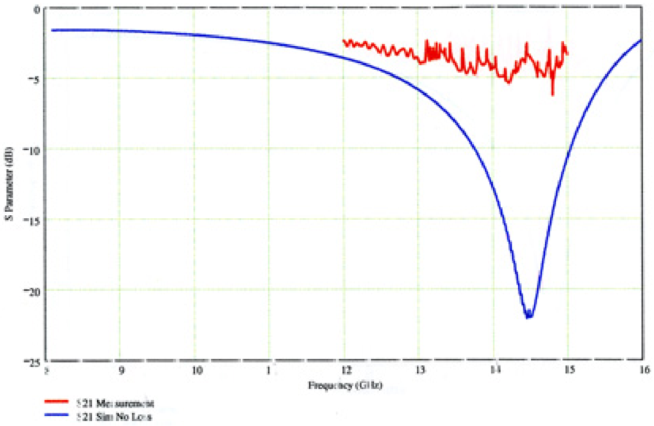
Sample 4 – 0.10mm stainless steel wire/ 2/24s cotton 3 picks



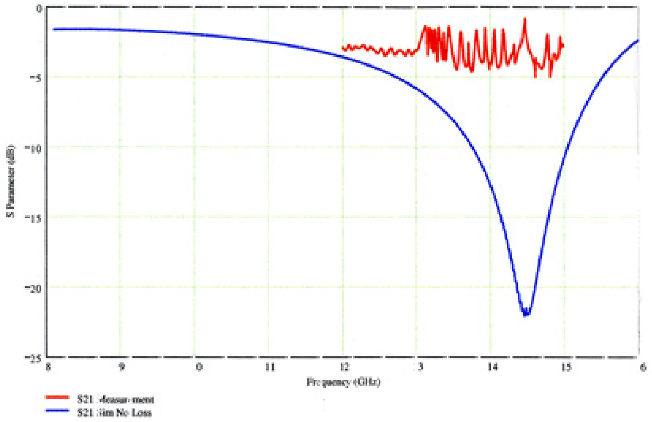
Sample 5 – 1 x 420 polypropylene / 1 x 30 X-Static – 10. 3 picks



Sample 6 – 1 x 100 grey polypropylene / 1x 30 / 1 ccw/ 5% X-Static. 4 picks



Sample 7 – 30 denier X-Static – only 10 strands. 18 picks.

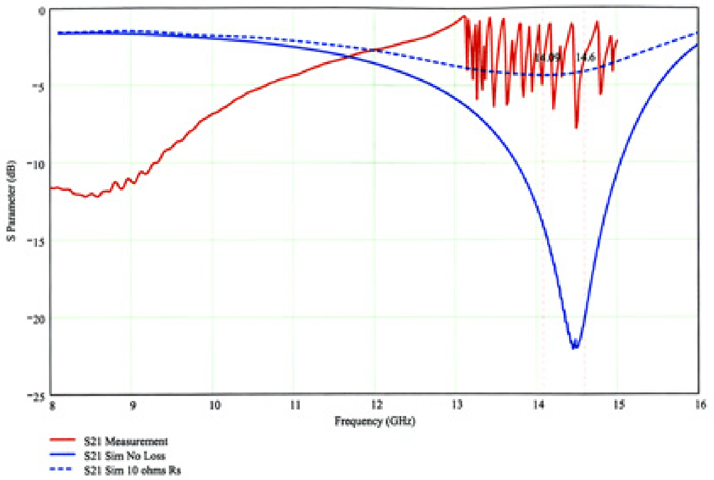


8.3 7MM LONG X-STATIC METALLISED WOVEN TRACK.

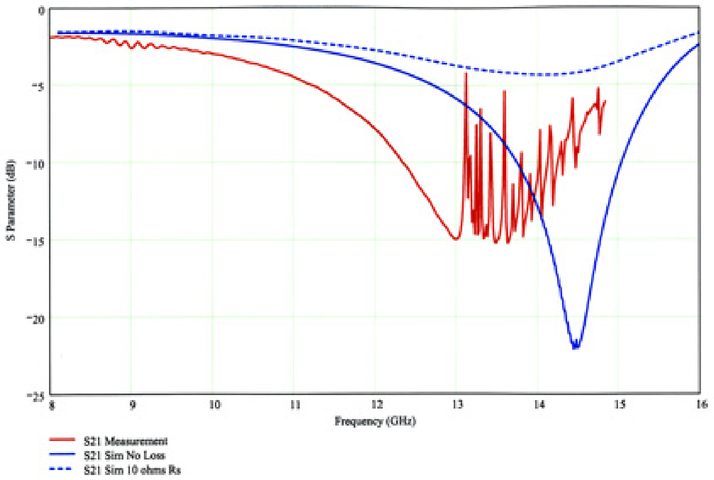
Samples were tested on 23rd February 2005

All samples are woven with a 2/40s cotton warp and weft.

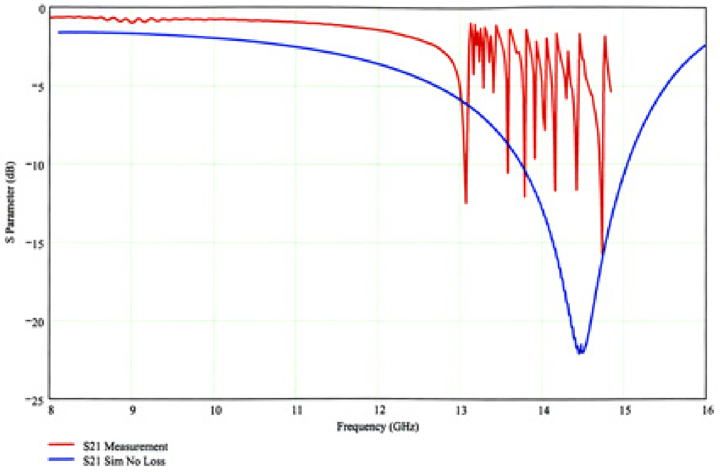
Sample 1 – 100 denier X-STATIC (70 + 30, 3m length) 10 picks



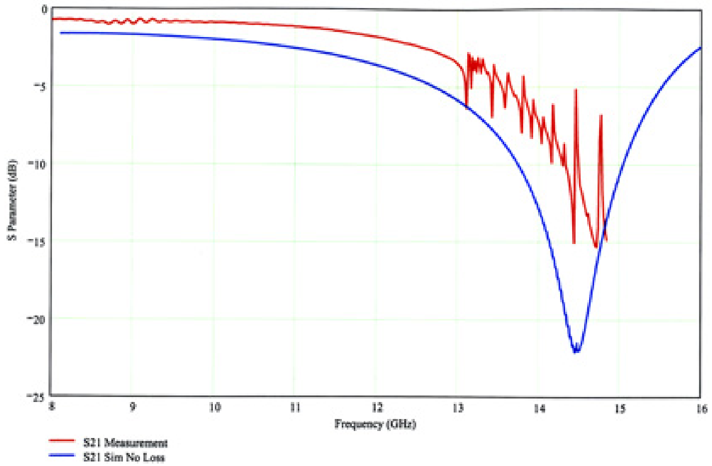
Sample 2 – 140 denier X-STATIC (70 +70, 3m length) 7 picks



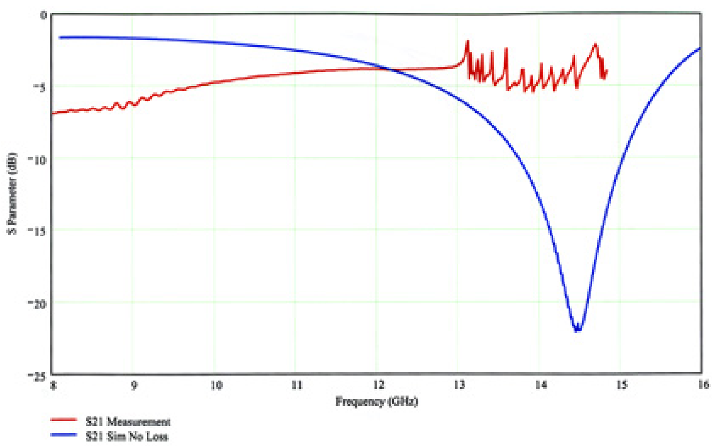
Sample 3 – 170 denier X-STATIC (70+70+30, 3m length) 5 picks



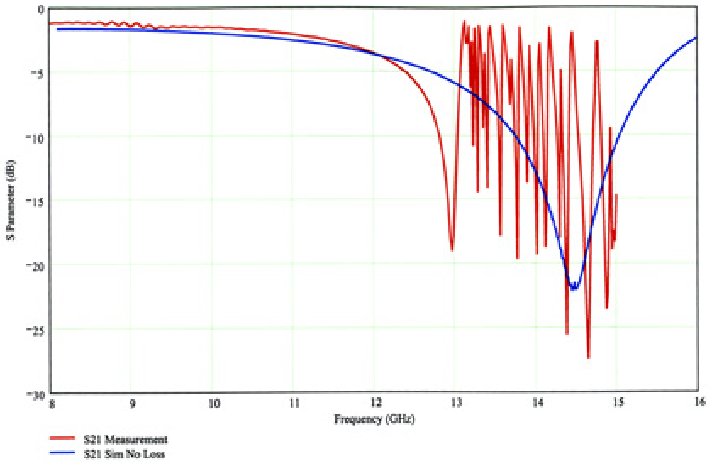
Sample 4 – 210 denier X-STATIC (70+70+70, 3m length) 4 picks



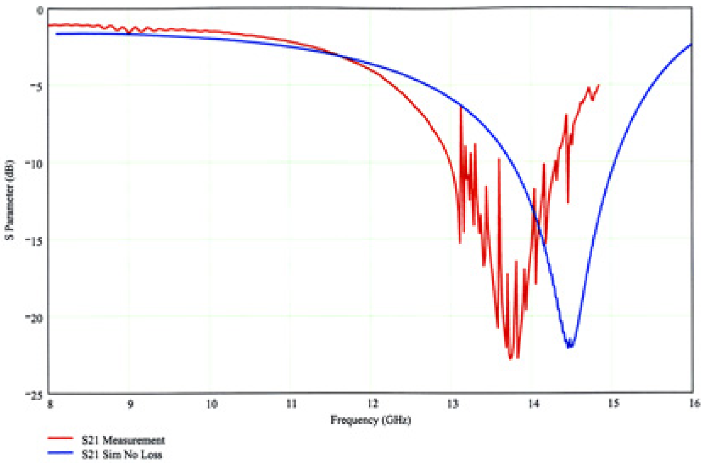
Sample 5 – 280 denier X-STATIC (70+70+70+70, 3m length) 4 picks



Sample 6 – 350 denier X-Static +60/66 ORGANZINE SILK (70+70+70+70+70 + 1x SILK,3m length) 3 picks .



Sample 7 – 200 denierX – STATIC (2 x 100 – XS – 34 , 2.5z.). 4 picks



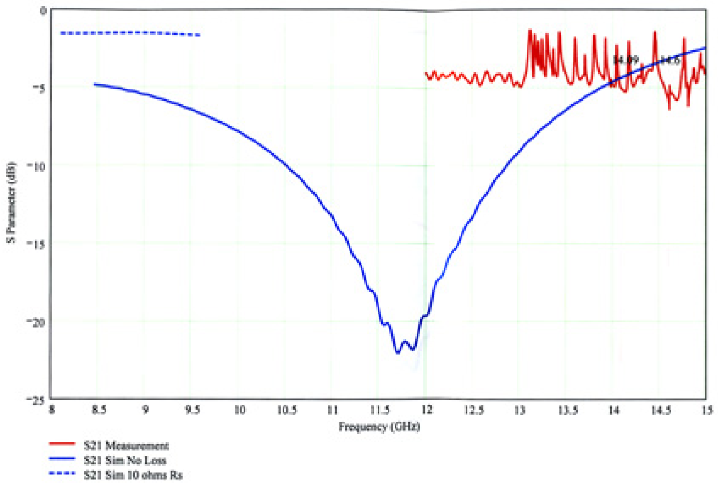
8.4 CONTINUAL 26MM X-STATIC METALISED LOOP

(2 x 7mm tracks in the weft and 2 x 6mm tracks in the warp)

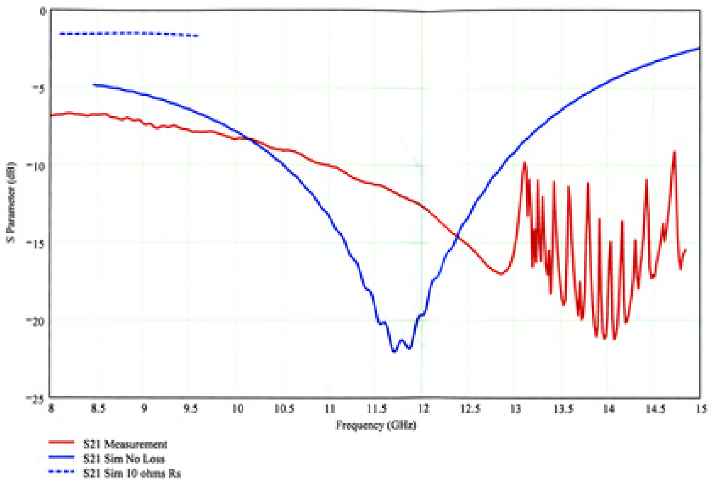
Samples were tested on <u>6 April 2005</u>

All samples are woven with a 2/40s cotton warp and weft.

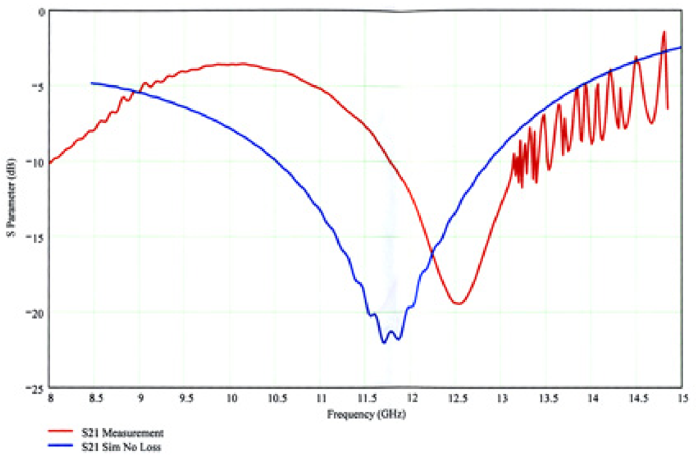
Sample 1 – 200 denier – 4 picks and 4 ends either side



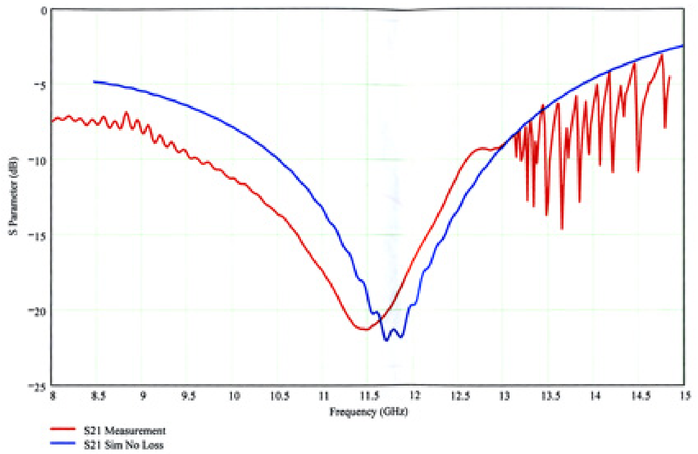
Sample 2 – 210 denier – 4 picks and 3 ends either side



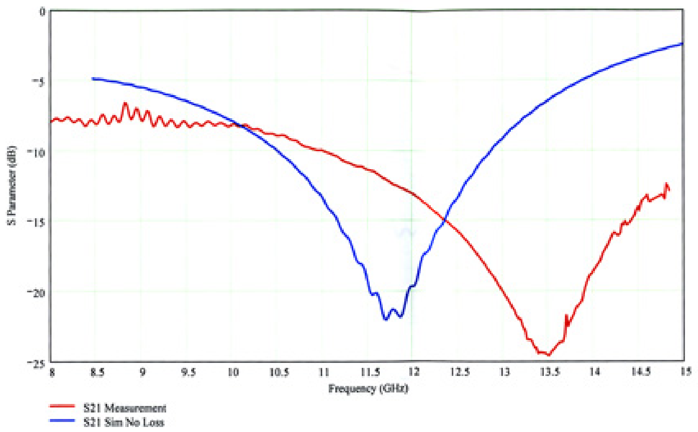
Sample 3 – 350 denier – 3 picks and 2 ends either side



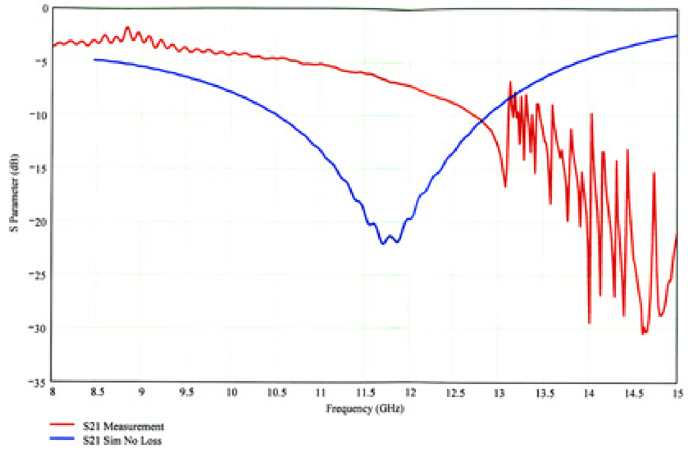
Sample 4 – 170 denier – 5 picks and 4 ends either side



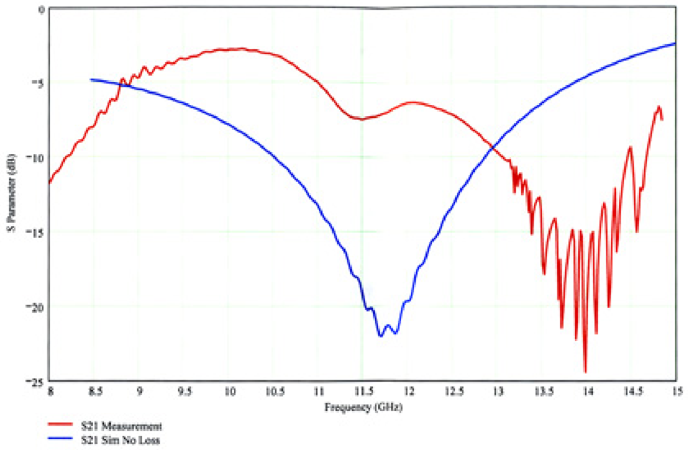
Sample 5 – 280 denier – 4 picks and 2 ends either side



Sample 6 – 140 denier – 7 picks and 4 ends either side

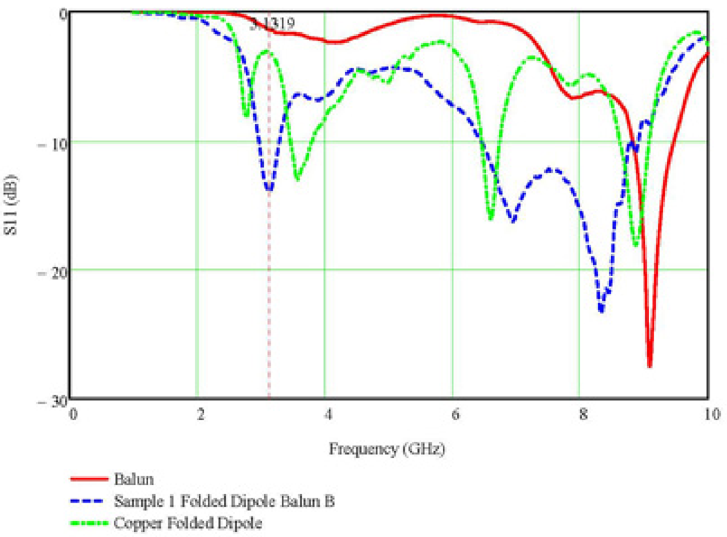


Sample 7 – 100 denier – 10 picks and 4 ends either side

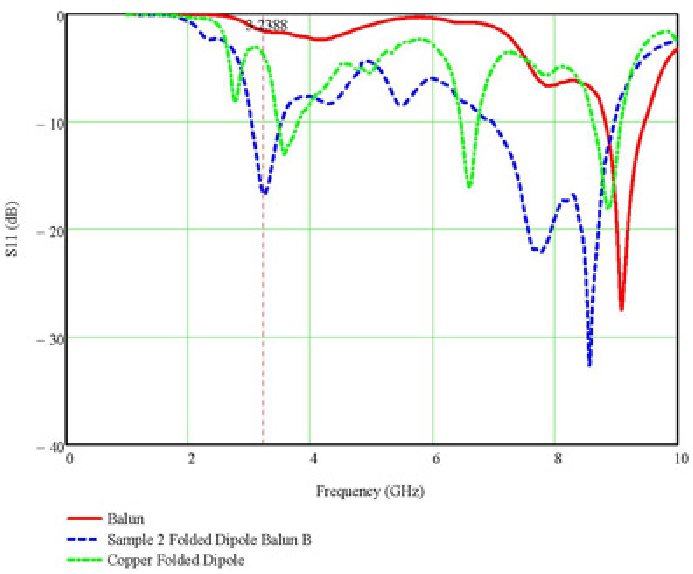


8.5 FOLDED DIPOLE ANTENNA MEASUREMENTS

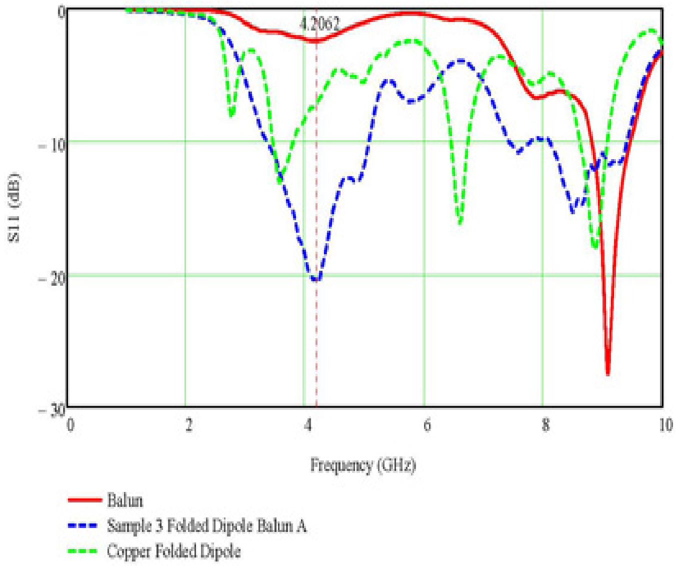
Sample 1



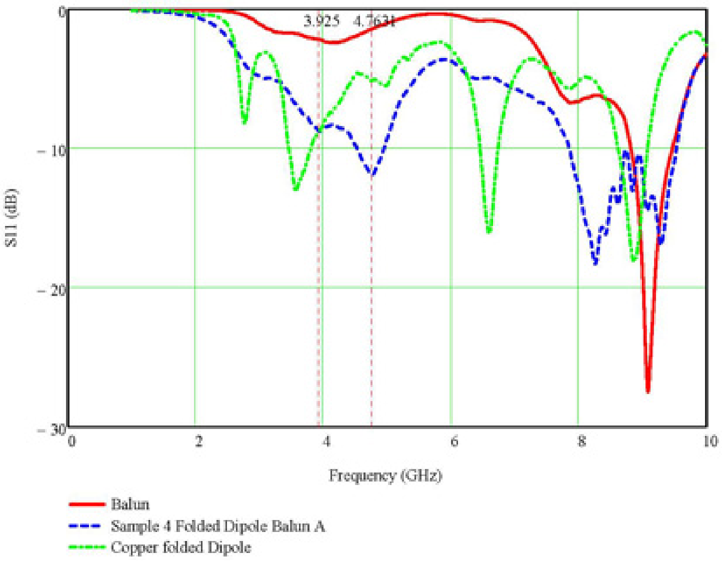
Sample 2



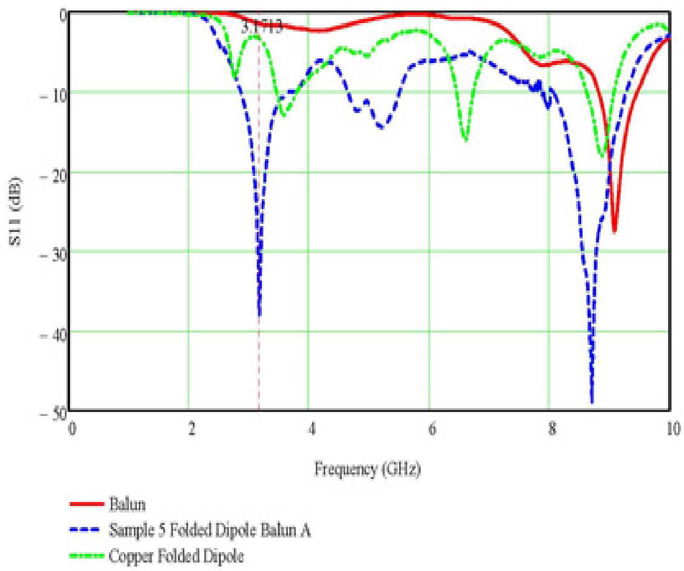
Sample 3



Sample 4

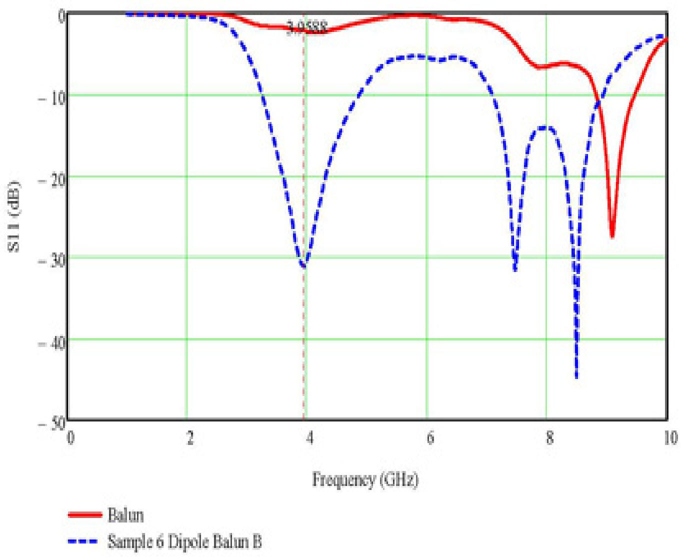


Sample 5

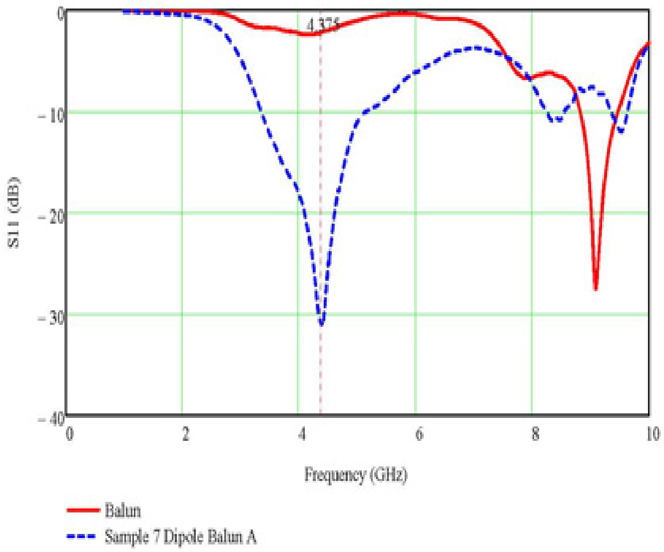


8.6 DIPOLE ANTENNA MEASUREMENTS

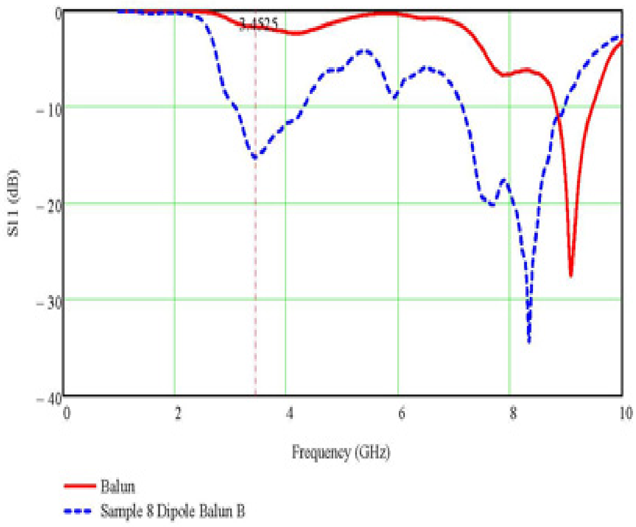
Sample 6



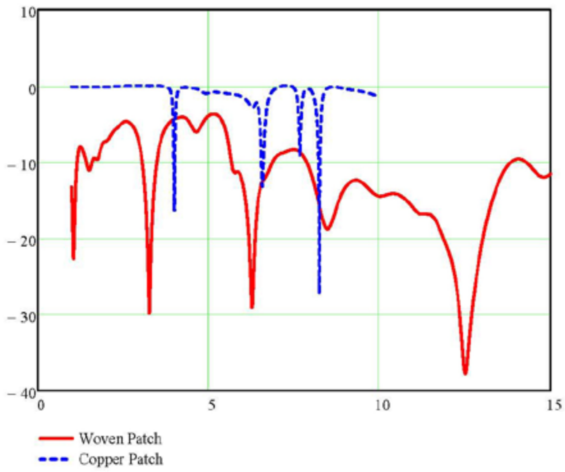
Sample 7

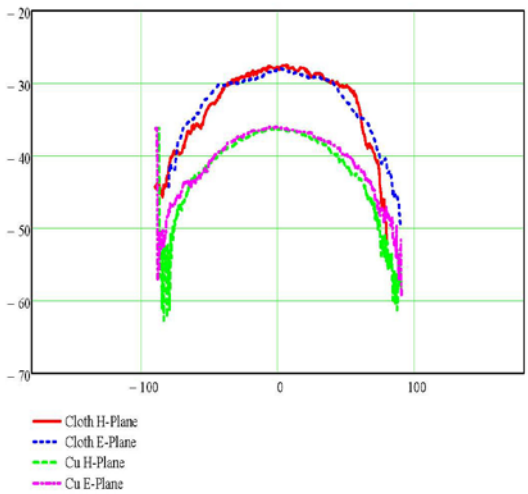


Sample 8

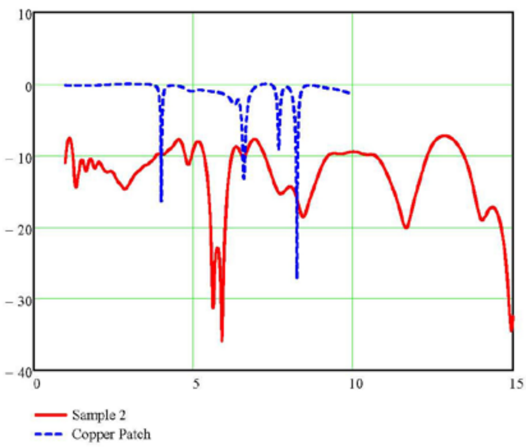


8.7 WOVEN PATCH ANTENNA RESULTS

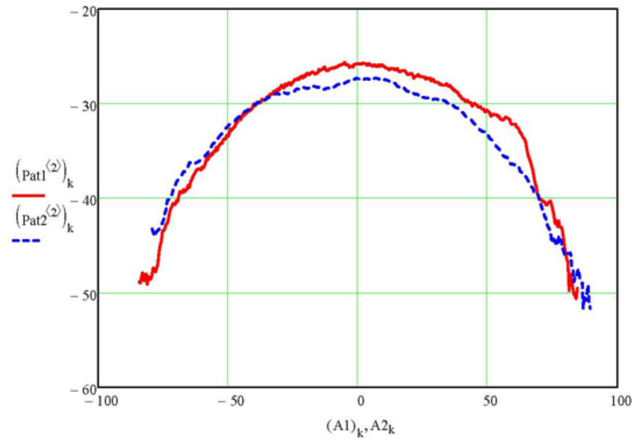


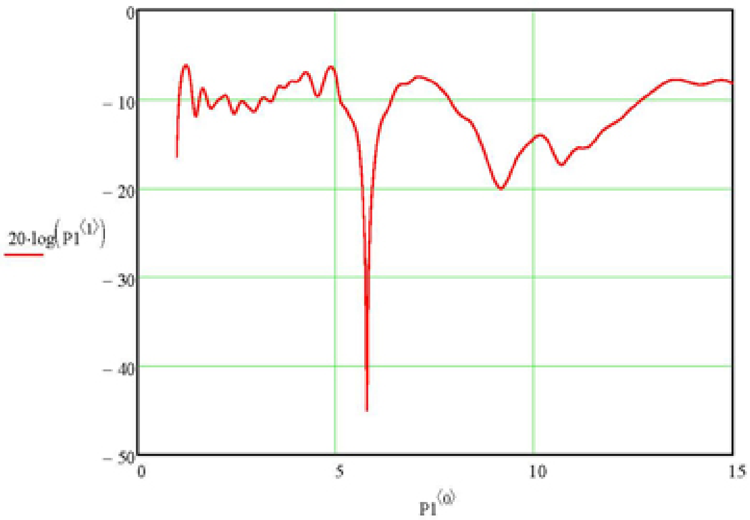


Sample 2 - 280 denier X-Static

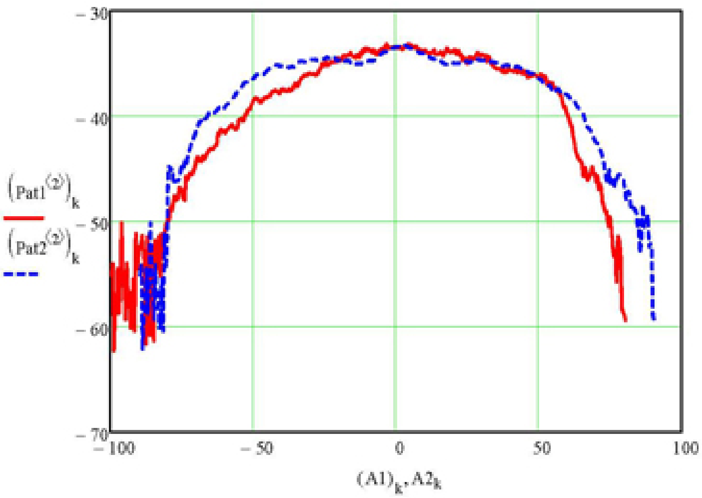


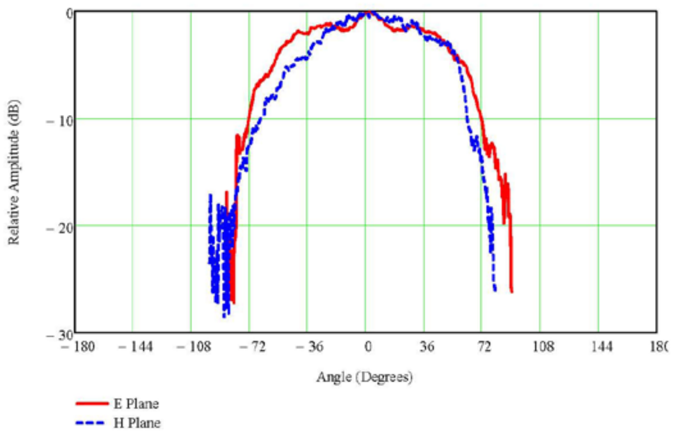
Sample 3 - 350 denier X-Static

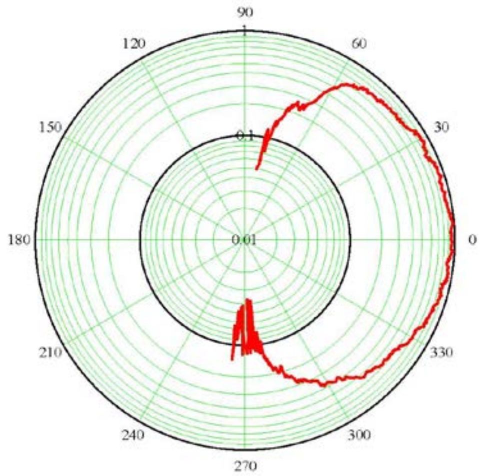




10 degree shift on Red 5.795GHz



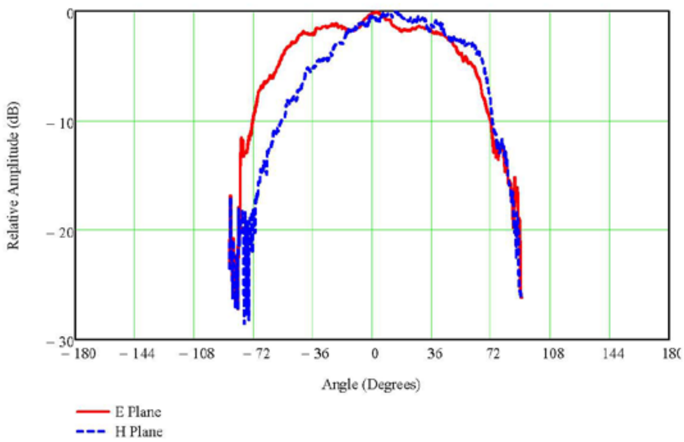


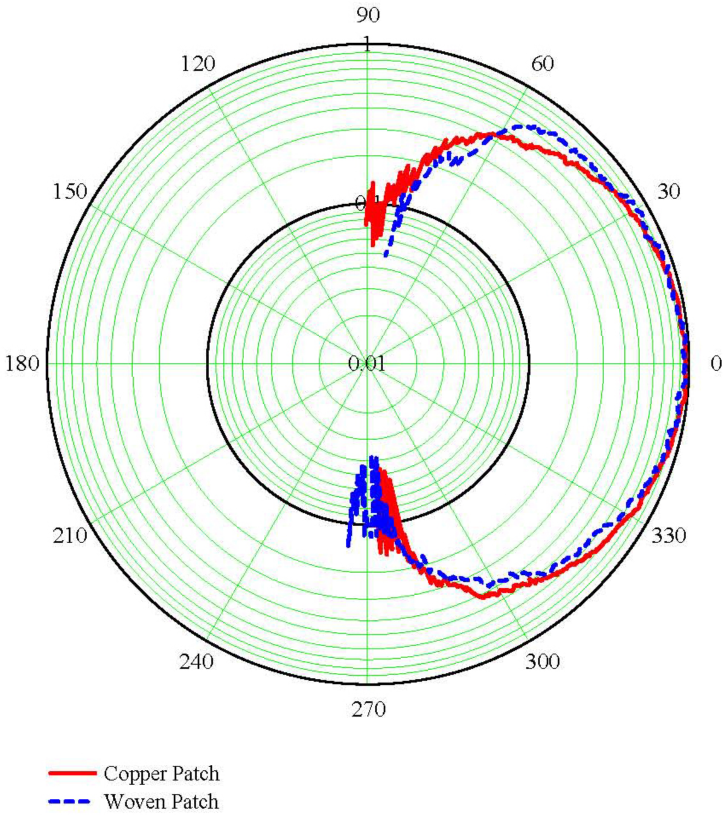


$D_3 :=$ ...\rds1.csv

$D_4 :=$ ...\rds2.csv

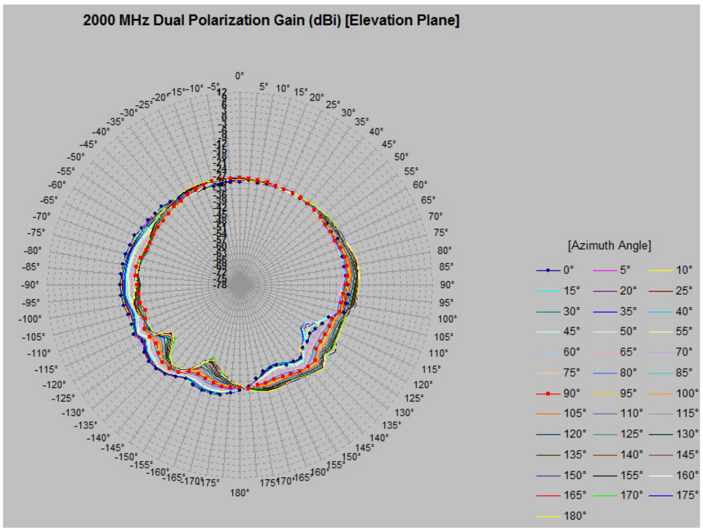
$A := D_3^{\langle 0 \rangle} \cdot \frac{18}{40} - 90$

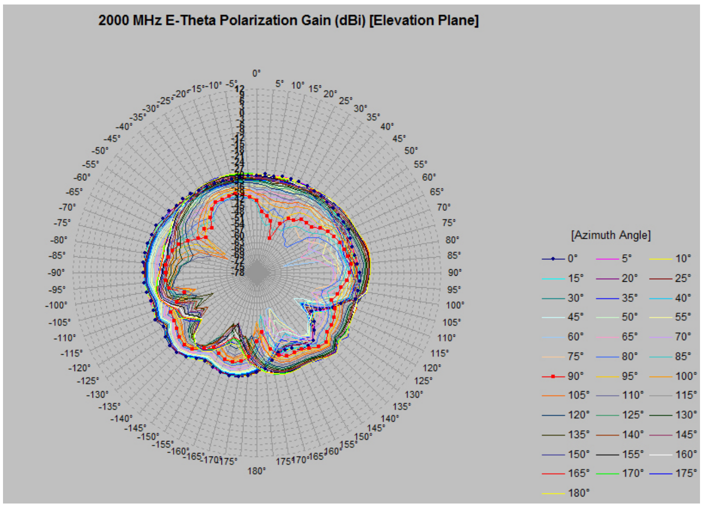


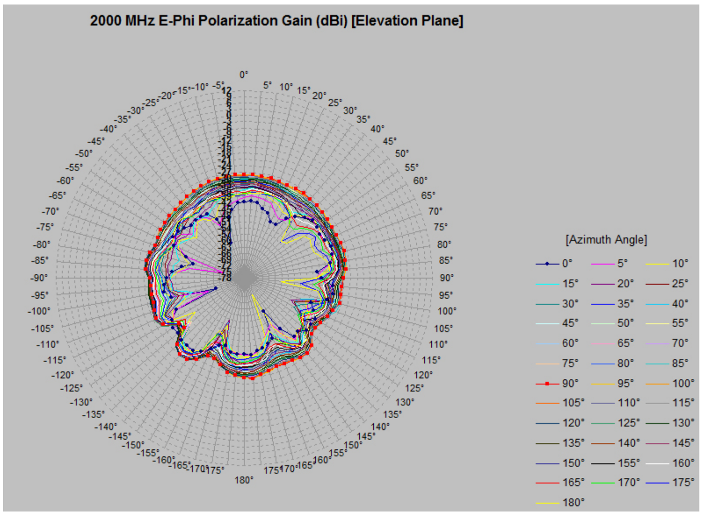

90
120
60
150
30
180
0
210
330
240
300
270
1
0.1
0.01
Copper Patch
Woven Patch

8.8 RESULTS OF PATCH ANTENNA WOVEN BY CASH'S
All results show Plot, E Theta and E Phi.

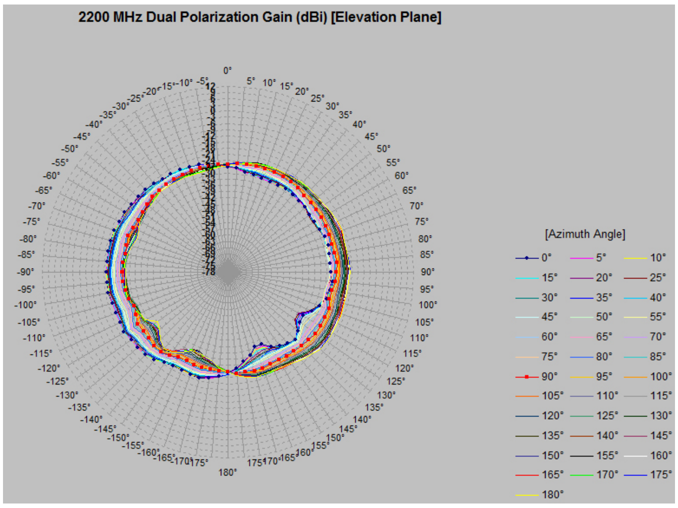
2000MHz

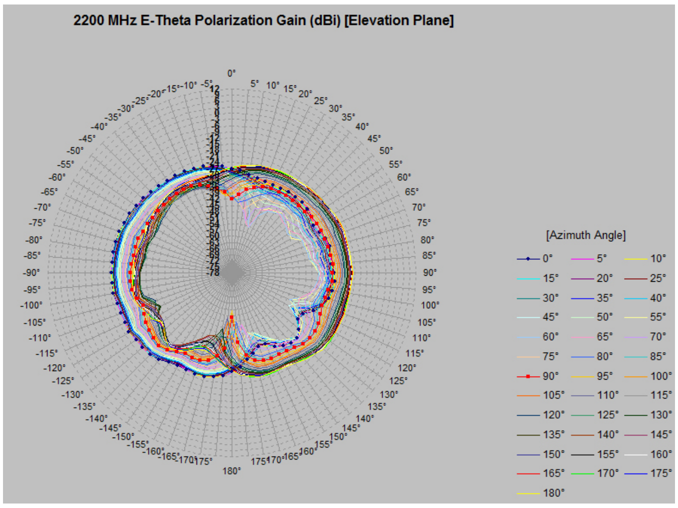


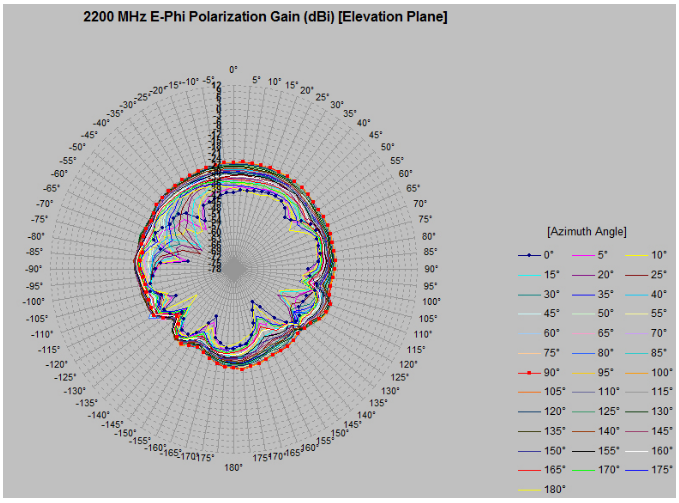




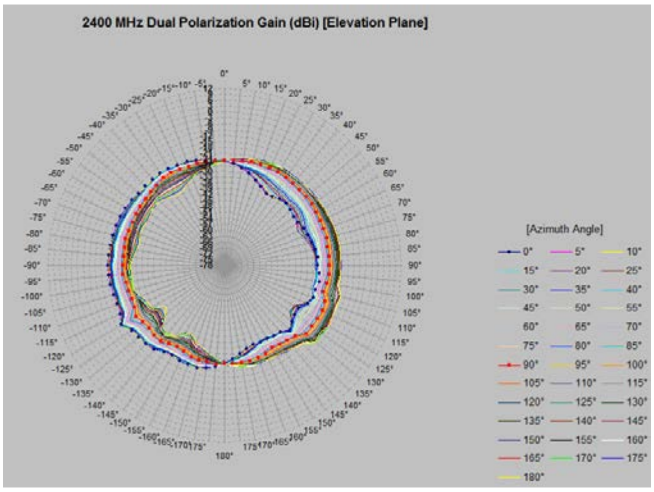
2200MHz

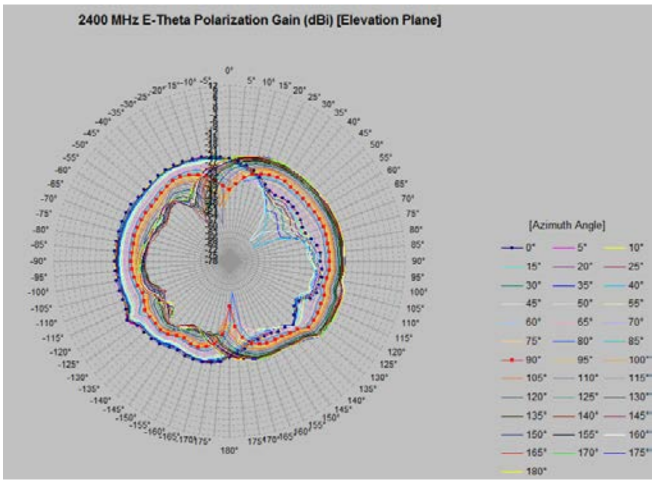

2200 MHz Dual Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]

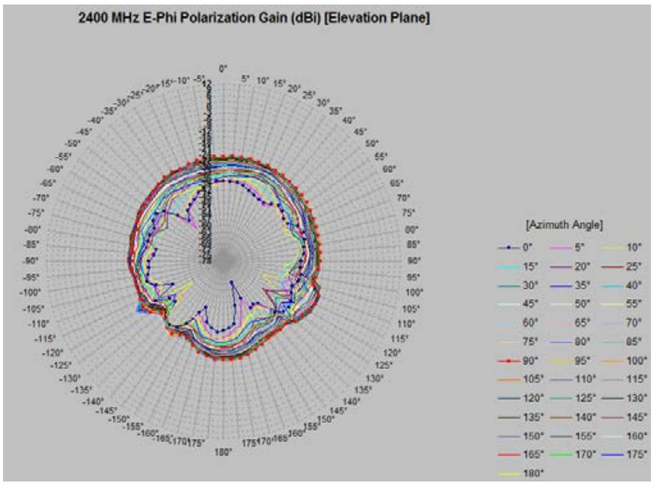

2200 MHz E-Theta Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]


2200 MHz E-Phi Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]

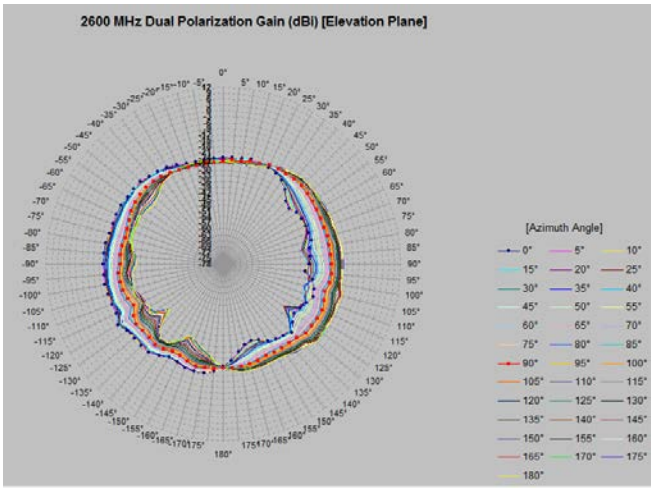
2400MHz

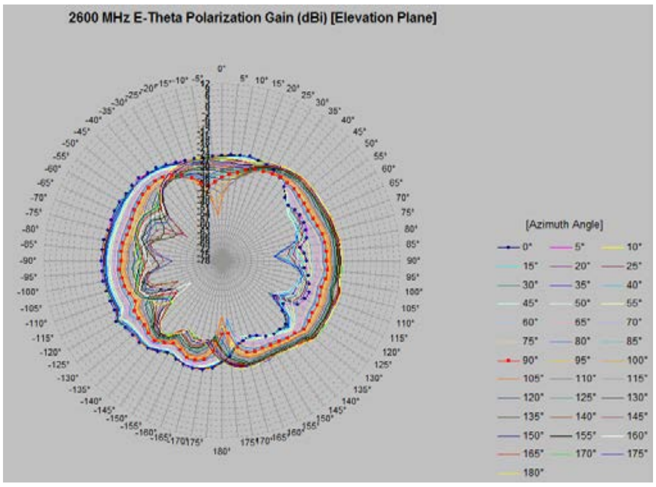

2400 MHz Dual Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]

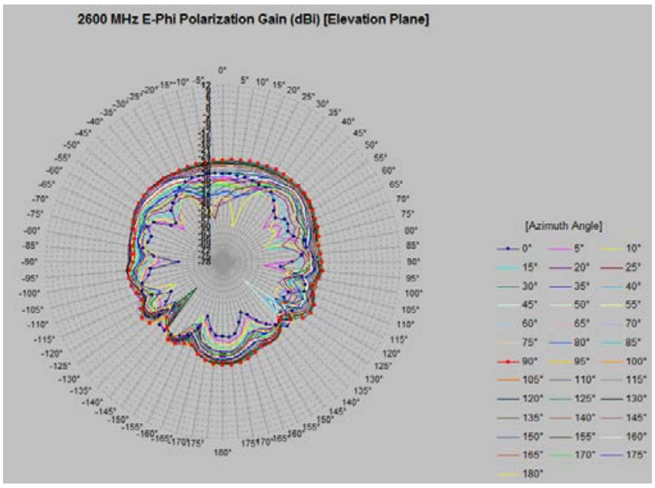

2400 MHz E-Theta Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]


2400 MHz E-Phi Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]

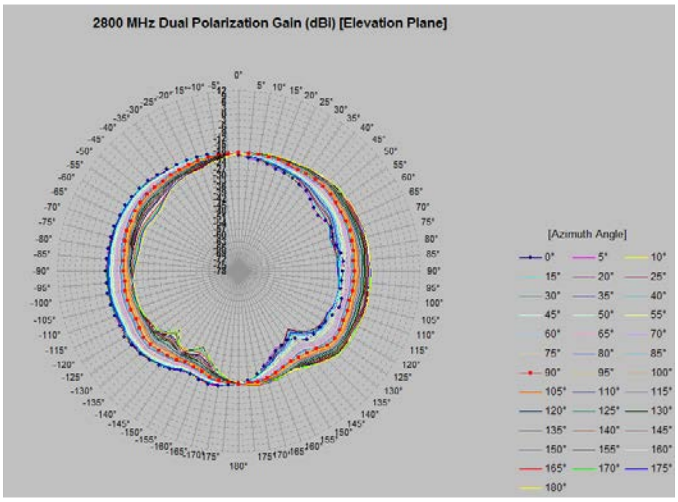
2600MHz


2600 MHz Dual Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]

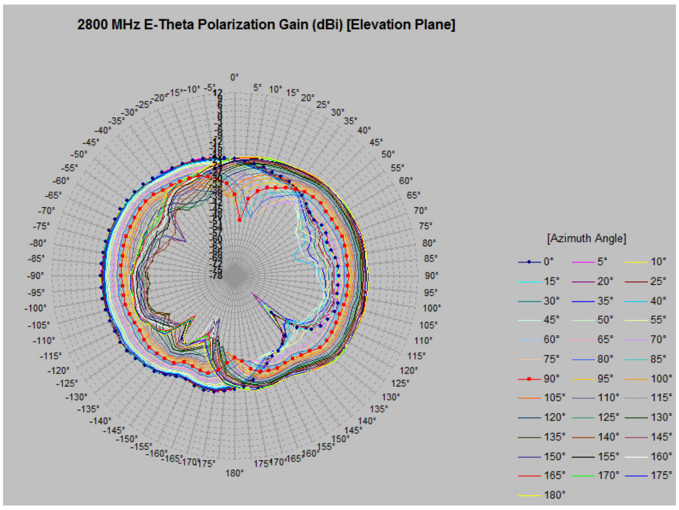

2600 MHz E-Theta Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]


2600 MHz E-Phi Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]

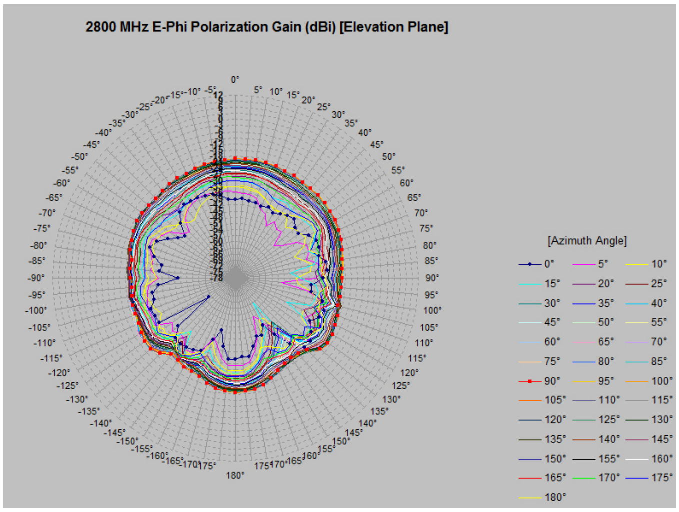
2800MHz



2800 MHz Dual Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]

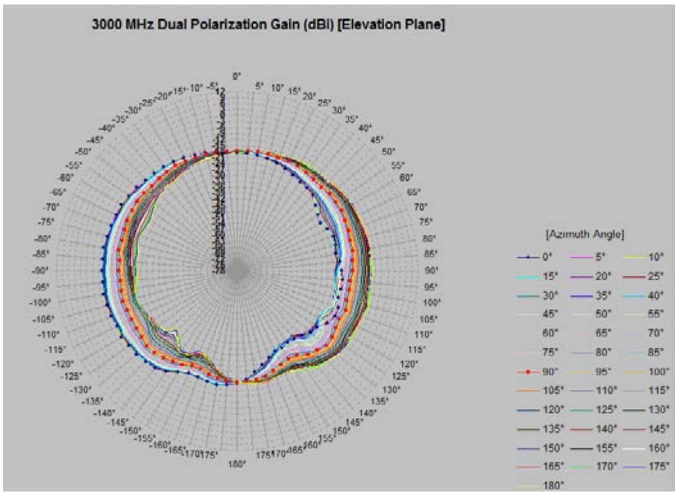


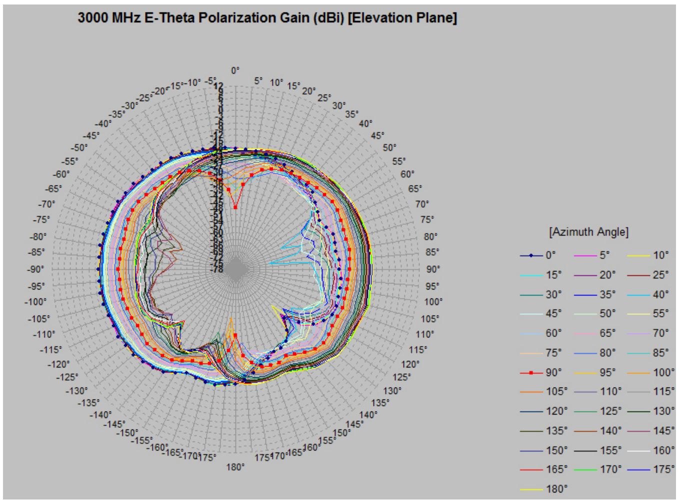
2800 MHz E-Theta Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]

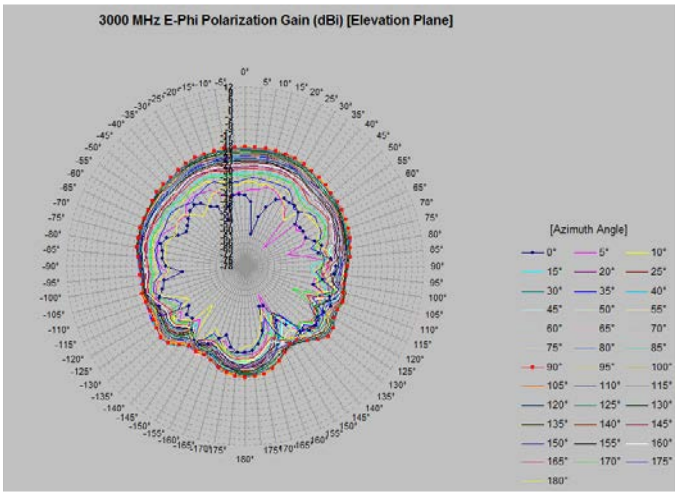


2800 MHz E-Phi Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]

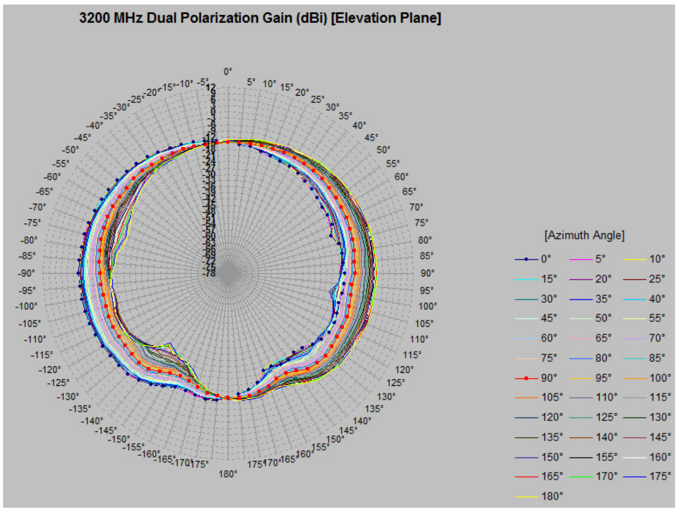
3000MHz

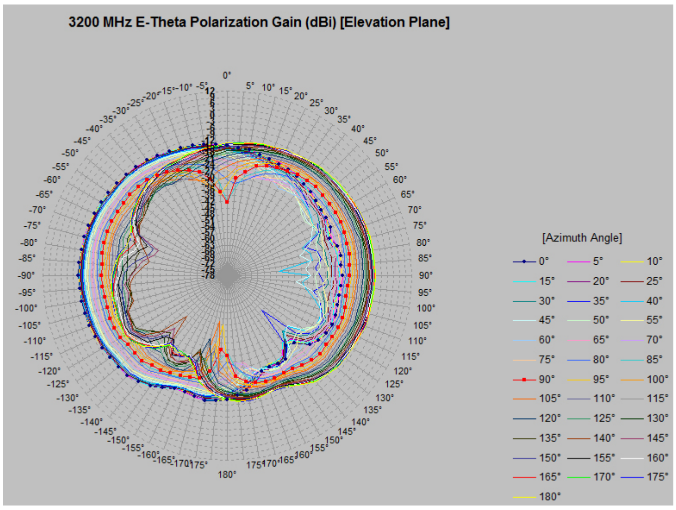

3000 MHz Dual Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]

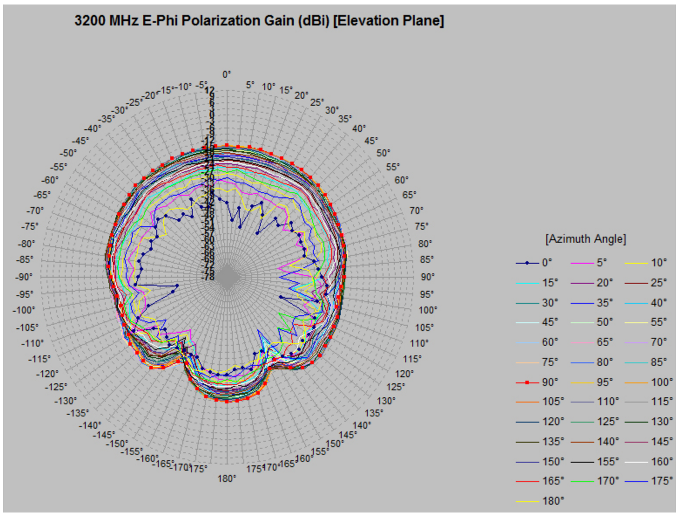

3000 MHz E-Theta Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]


3000 MHz E-Phi Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]

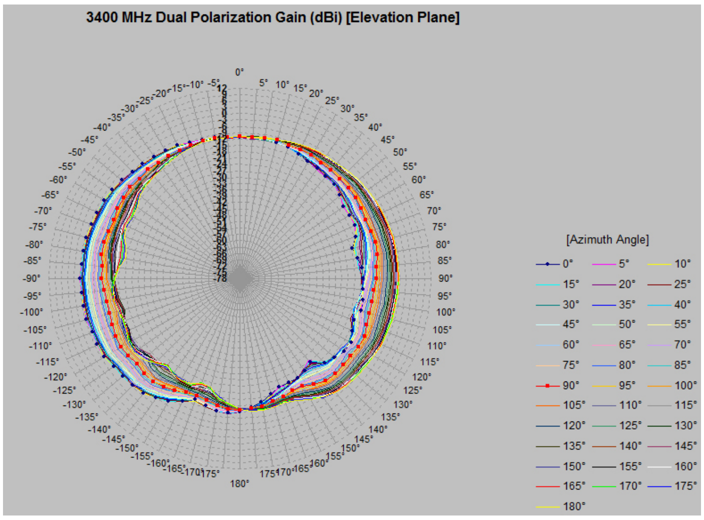
3200MHz

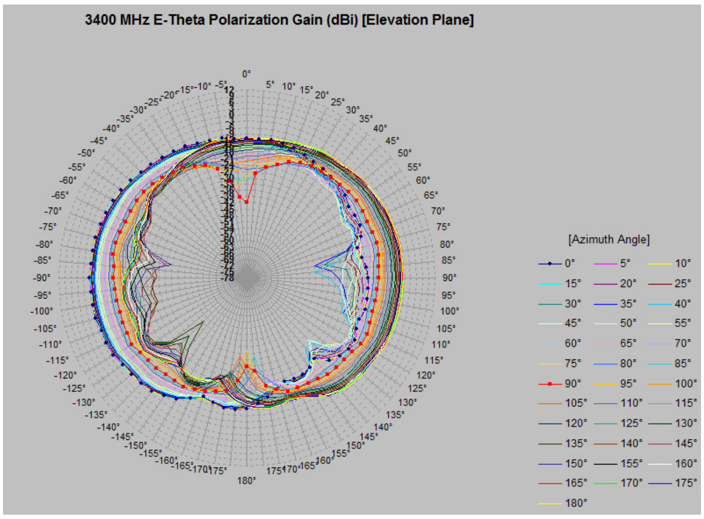

3200 MHz Dual Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]

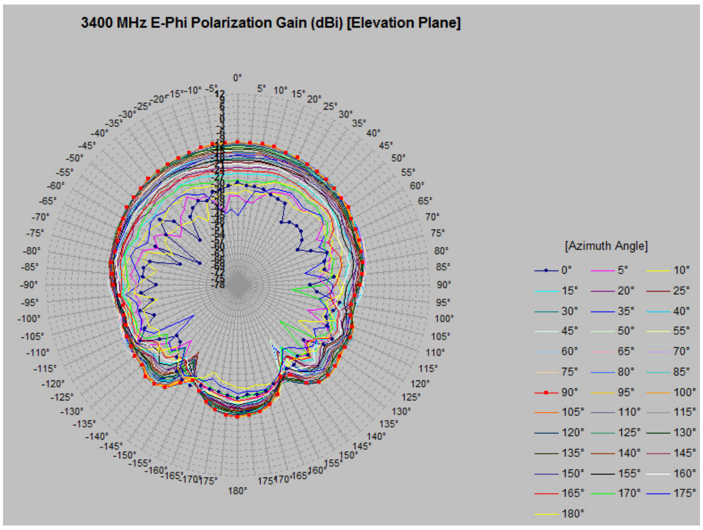

3200 MHz E-Theta Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]


3200 MHz E-Phi Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]

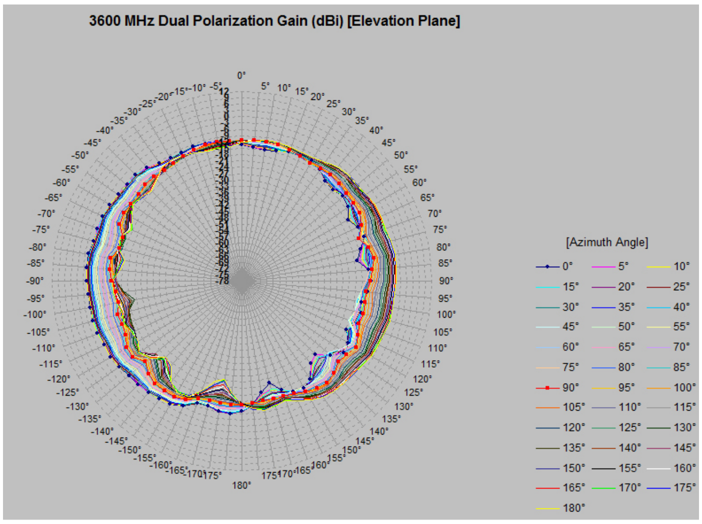
3400MHz

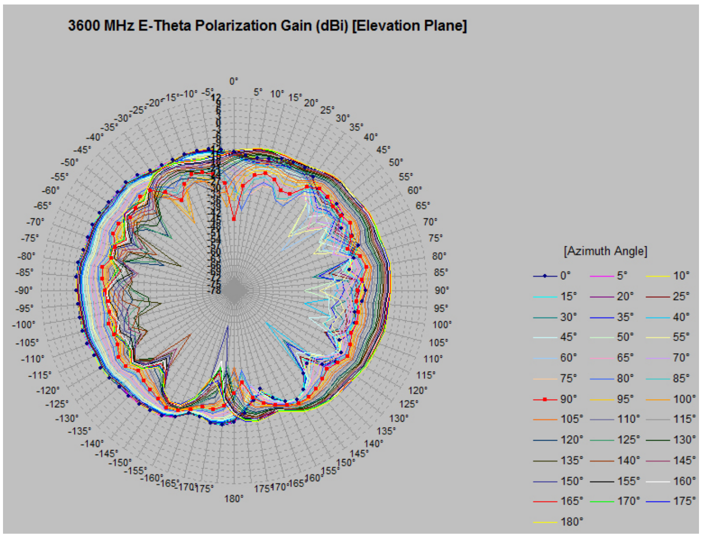

3400 MHz Dual Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]
0° 5° 10° 15° 20° 25° 30° 35° 40° 45° 50° 55° 60° 65° 70° 75° 80° 85° 90° 95° 100° 105° 110° 115° 120° 125° 130° 135° 140° 145° 150° 155° 160° 165° 170° 175° 180°

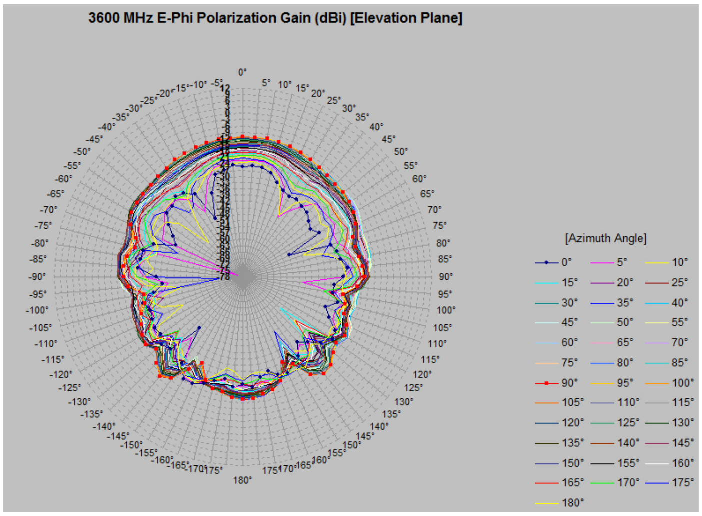

3400 MHz E-Theta Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]
0° 5° 10° 15° 20° 25° 30° 35° 40° 45° 50° 55° 60° 65° 70° 75° 80° 85° 90° 95° 100° 105° 110° 115° 120° 125° 130° 135° 140° 145° 150° 155° 160° 165° 170° 175° 180°


3400 MHz E-Phi Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]
0° 5° 10° 15° 20° 25° 30° 35° 40° 45° 50° 55° 60° 65° 70° 75° 80° 85° 90° 95° 100° 105° 110° 115° 120° 125° 130° 135° 140° 145° 150° 155° 160° 165° 170° 175° 180°

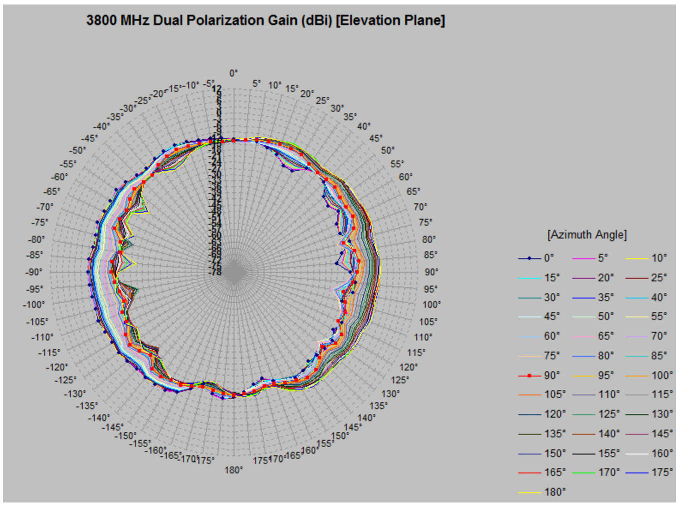
3600MHz

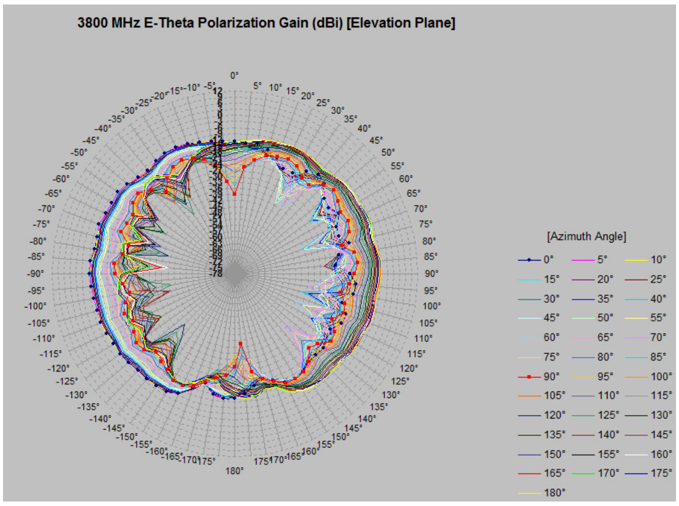

3600 MHz Dual Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]
0° 5° 10°
15° 20° 25°
30° 35° 40°
45° 50° 55°
60° 65° 70°
75° 80° 85°
90° 95° 100°
105° 110° 115°
120° 125° 130°
135° 140° 145°
150° 155° 160°
165° 170° 175°
180°

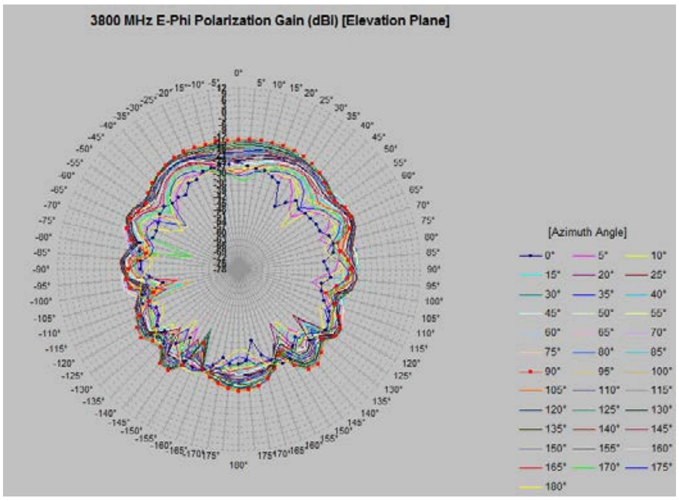

3600 MHz E-Theta Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]
0° 5° 10°
15° 20° 25°
30° 35° 40°
45° 50° 55°
60° 65° 70°
75° 80° 85°
90° 95° 100°
105° 110° 115°
120° 125° 130°
135° 140° 145°
150° 155° 160°
165° 170° 175°
180°


3600 MHz E-Phi Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]
0° 5° 10°
15° 20° 25°
30° 35° 40°
45° 50° 55°
60° 65° 70°
75° 80° 85°
90° 95° 100°
105° 110° 115°
120° 125° 130°
135° 140° 145°
150° 155° 160°
165° 170° 175°
180°

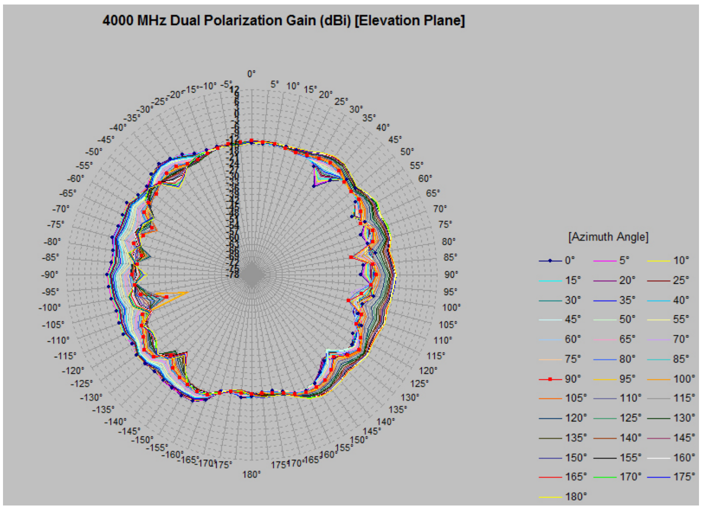
3800MHz


3800 MHz Dual Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]


3800 MHz E-Theta Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]


3800 MHz E-Phi Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]

4000MHz


4000 MHz Dual Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]
0°
5°
10°
15°
20°
25°
30°
35°
40°
45°
50°
55°
60°
65°
70°
75°
80°
85°
90°
95°
100°
105°
110°
115°
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130°
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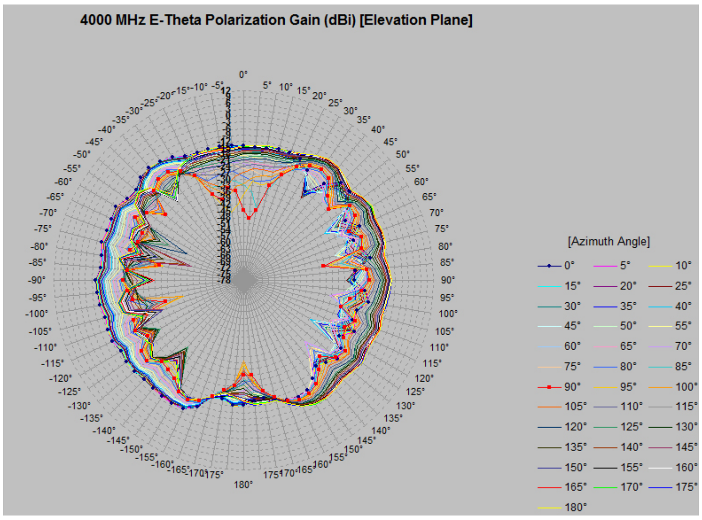
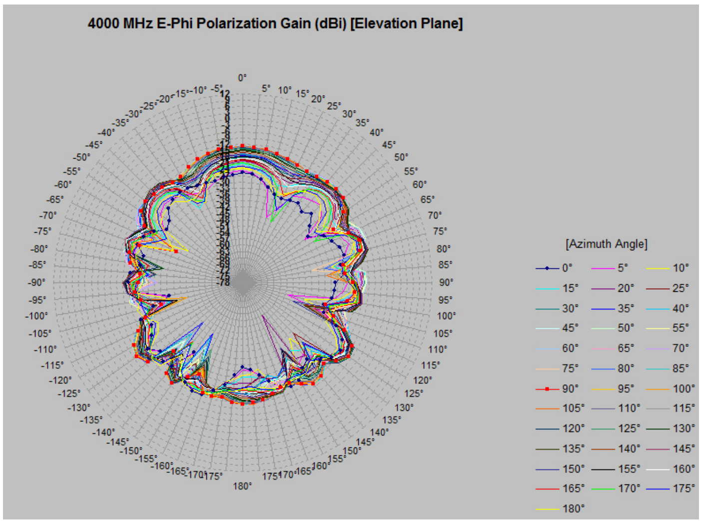
140°
145°
150°
155°
160°
165°
170°
175°
180°


4000 MHz E-Theta Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]


4000 MHz E-Phi Polarization Gain (dBi) [Elevation Plane]
[Azimuth Angle]

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10 ILLUSTRATIONS

11 PROFESSIONAL DEVELOPMENT COURSES ATTENDED

Postgraduate Research Students Induction

Keeping Your Research Up-to-Date for Science and Engineering Postgraduates

Reading for Research

Tracing Journal Articles for Science and Engineering Postgraduates

Teaching Skills for Postgraduates and Research Assistants

Report Writing