NOVEL HIGH FREQUENCY ELECTROMAGNETIC SHIELDING
MEASUREMENTS WITHIN FUNCTIONAL GEOMETRIES USING NON-METAL
AND FATIGUED CONDUCTORS

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ABSTRACT

NOVEL HIGH FREQUENCY ELECTROMAGNETIC SHIELDING MEASUREMENTS WITHIN FUNCTIONAL GEOMETRIES USING NON-METAL AND FATIGUED CONDUCTORS

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The purpose of this research was to develop novel nanoparticle-enabled material shields and conductors for use in electrical coaxial cables, and to create appropriate methods to characterize their response to high frequency electromagnetic fields. In addition, techniques to distinguish the effects of mechanical degradation on electrical properties were developed.

Traditional electrical measurements methods are ineffectual to such characterization due to limitations with frequency range, sample geometry, field impingement, and false assumptions of field coupling to non-metal center conductors. In this study, a reverberation chamber was used to develop a novel measurement method using conduction characterizations from a network analyzer. Samples were fatigued to identify the effects of heavy use and mechanical degradation on shielding effectiveness and...
system characterization, including impedance, voltage standing wave ratio, return loss, and insertion loss. The novel measurement of shielding effectiveness as well as system characterizations was used to determine the effect of material properties on cabling functionality, both electrical and mechanical and their inter-relationship.

The results showed that the combination of carbon nanotube yarn center conductors and carbon nanotube tape shields led to more signal attenuation and therefore much higher characteristic impedance. Utilizing the novel method to measure the shielding effectiveness allowed for the incorporation of these differences in power transmission while simultaneously analyzing the immunity of the three-dimensional shield within a high frequency field. The carbon nanotube tape shields provided lightweight and efficient shielding at higher frequencies (towards 5 GHz) due to a decreasing skin depth at higher frequencies. A braid architecture, that which was incorporated in the silver coated copper clad steel shield, proved to withstand mechanical fatigue better, while the carbon nanotube helical tape began to stretch apart. This was because the braid better axially supported the load and began to tighten, reducing the size of apertures in many instances. Though it is possible for the conductivity of carbon nanotube bulk materials to improve due to fatigue or tension, no over-arching trends were observed to have an effect of shielding post fatigue.
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<tbody>
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<td>A</td>
<td>Ampere(s)</td>
</tr>
<tr>
<td>CNT</td>
<td>Carbon Nanotube</td>
</tr>
<tr>
<td>dB</td>
<td>Decibel(s)</td>
</tr>
<tr>
<td>E</td>
<td>Energy</td>
</tr>
<tr>
<td>ε</td>
<td>Permittivity</td>
</tr>
<tr>
<td>F</td>
<td>Farad(s)</td>
</tr>
<tr>
<td>k</td>
<td>Wave number</td>
</tr>
<tr>
<td>h</td>
<td>Planck’s constant</td>
</tr>
<tr>
<td>Hz (MHz, GHz)</td>
<td>Hertz (Megahertz, Gigahertz)</td>
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<td>I</td>
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<td>σ</td>
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<tr>
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<td>V</td>
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<td>Z</td>
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CHAPTER 1

INTRODUCTION

1.1 Background

Traditional composite materials and nano-enabled materials are becoming increasingly utilized within the aircraft, aerospace, and transportation industries for a variety of reasons. In these fields and others, the most predominate reason such materials are appealing is for the combination of low density, desirable mechanical/strength improvements and electrical properties. In some cases, these properties approach traditional metals and the viability for replacements in many systems become much more plausible.

Such may be the case for electrical circuitry and communication lines, which are traditionally constructed utilizing a metal center line conductor as well as a concentric metal shield. Because traditional electromagnetic shielding materials already have a history of detrimental failures due to electromagnetic interference, it is imperative that any potential replacement both conducts and protects electrical signals, even at higher frequencies. In addition, because much componentry also fails due to mechanical fatigue, utilizing resilient materials that minimize performance degradation due to cycling of stresses is ideal. All of these aspects should be evaluated as a part of the complex coaxial cable geometry, in order to best engineer suitable materials for their application.
1.2 Problem Description

A common error made with investigating novel materials as a constituent of multi-part systems is that most practical test methods rely on properties of metals to make accurate measurements. Nano-enabled materials, however, do not conduct electricity across a wide band of frequencies the same way as metals due to difference in their microstructures and architecture.

In the case of electromagnetic susceptible circuitry, all aspects of the structure (centerline conductor and shielding) need to be considered in realistic conditions, which implies randomly polarized electromagnetic radiation with multiple angles of incidence. Also, conditions must be repeatable. A mode-stirred reverberation chamber offers such an environment. This research will evaluate several novel as well as traditional materials as components within a coaxial cable geometry utilizing a mode-stirred chamber. Nano materials and metals will be studied both as shields and conductors, and the nature of both materials within high frequency fields as well as their interaction will be elucidated.

1.3 Research Objectives

The goal of this research is to explore electromagnetic shielding phenomena and tensile fatigue of conductor and shield materials within the coaxial cable geometry. This will involve the following elements:

1) First, centerline conductor materials will be characterized within the coaxial system to determine the mechanisms responsible for attenuation.

2) Next, each conductor-shield system will be mechanically fatigued in order to evaluate durability.
3) Because mechanical fatigue may affect performance of the center conductor as well as the shield, this study will develop a novel experimental procedure by which to quantify the influence of fatigue on the signal carrying capability of the coaxial system.

4) An explanation for the increase in shielding effectiveness observed in novel carbon nanomaterial shields (around 5GHz) will be developed by means of experimentation/material characterization and/or justification from literature.

5) The physical mechanisms responsible for the mechanical fatigue within each coaxial cable type will be elucidated. This will be used to isolate the effect of material properties and architecture on objectives 1-4 above.

The culmination of this research is the development of a shielding effectiveness measurement method for as-manufactured shielding materials and/or fatigued coaxial system within high frequency electromagnetic fields using a mode-stirred reverberation chamber.
CHAPTER 2
REVIEW OF LITERATURE

2.1 Definition of Key Terms

Carbon Nanofiber (CNF) – A nanometer scale cylindrical structure of graphene layers in cup, cone, or plate arrangements.

Carbon Nanotube (CNT) – A nanometer scale tubular structured allotrope of carbon known for their high aspect ratio (length to diameter) and subsequently unique properties.

Characteristic Impedance ($Z_0$) – The ratio of voltage and current amplitudes for a uniform transmission line in the absence of reflections; characteristic impedance is independent of length and dependent on the materials and line geometry.

Coaxial Cable – A type of cable with tubular inner conductor and outer conductor and an insulating layer in between all along the same geometric axis (that is, coaxial).

Conductor – A material or device with a high capability to transmit, in this case, electricity (can also be with respect to heat or sound).

Decibel (dB) – Logarithmic unit of measure, which gives the ratio of power to a specified reference level. In the case of decibel-milliwatt (dBm), it is the power expressed with reference to one milliwatt.
Egress – The action of, in this case, electrical signal leaving an enclosure.

Electromagnetic Interference (EMI) - The disturbance caused by external electromagnetic sources that can couple into electrical circuitry and trigger unintended signal response.

Emission – The release of, in this case, electromagnetic energy from a material, device, or enclosure.

Faraday Cage – A conducting enclosure or screen that is used to block electromagnetic fields.

Frequency (f) – The rate of repetition of something over a given period of time, in this case the rate of waves of electromagnetic energy (in the form of electrical signal or alternating field), per second.

Impedance (Z) - Within alternating current circuits, a complex measure of opposition to current when a voltage is applied, akin to resistance within direct current measurements.

Ingress – The action of, in the case, electromagnetic energy entering an enclosure.

Insertion Loss – The loss of signal power associated with the insertion of a device, transmission line, or optical fiber, into a circuit.

Return Loss – The loss of signal associated with returned/reflected power due to discontinuities or mismatched load.

Radiation – The emission or transmission of electromagnetic waves or particles.
Reverberation Chamber – (Also known as mode stirred chamber) An electromagnetic compatibility testing environment that creates a statistically isotropic, randomly polarized electromagnetic field.

Voltage Standing Wave Ratio – The ratio of the peak to trough amplitude of the voltage signal which due to the presence of constructive or destructive interference indicates how well matched a coaxial system is (in a matched system the voltage standing wave ratio will be one).

### 2.2 Electromagnetic Interference

Electromagnetic interference or radio frequency interference is the disturbance caused by external sources that can couple into electrical circuitry and trigger unintended signal response. Although traditional metal shields can be employed to help mitigate such interference, they can often have negative consequences including excessive weight, failures due to electromagnetic disturbances, and they are prone to mechanical degradation especially under fatigue. Novel materials, particularly nanoscopic forms of carbon such as nanotubes or graphene with tunable electronic properties, offer an encouraging new material alternative not only as a shield but even as a conductor.

With a growing reliance on electronic devices, for communication with critical functions in both military and consumer applications, preventing disruption to and from devices has become an exponentially increasing concern. Electromagnetic interference (EMI), originates from “sources [such as] static sparks, lightning, radar, radio and TV transmission, brush motors, line transients, etc. By line conduction or air propagation, electromagnetic interference can induce undesirable voltage signals in electronic
equipment causing incorrect readings on sensors or instruments and occasionally component damage. Protection against electromagnetic interference usually requires the use of shields, filters, and special circuit design.” [1].

Electromagnetic interference can range in frequency, as seen in Figure 2.1. Frequency is the number of repetitions of a periodic process in a unit of time: as: a: the number of complete alternations per second of an alternating current or b: the number of complete oscillations per second of energy (as sound or electromagnetic radiation) in the form of waves [2].

![The Electromagnetic Spectrum](image)

**Figure 2.1:** The Electromagnetic Spectrum. (Reproduced with Permission of the Advanced Light Source, Lawrence Berkeley National Laboratory) [3].

Sources can have bandwidths (the range of frequencies covered) that are broadband or narrowband in frequency. Broadband EMI sources emit a wider band of frequencies and tend to be from sources such as electric power transmission lines. Narrowband
electromagnetic interference usually comes from sources that typically are designed to emit a specific frequency such as radio stations or cell phones. Electromagnetic interference can occur due to low or high frequency fields.

Electromagnetic emission can be intentional or unintentional in nature, both of which can have hazardous effects. Unintentional sources emit electromagnetic interference as a byproduct of their design; this includes devices such as toaster ovens, electric motors, and bug zappers. Interference can come from natural sources as well, such as the sun or the northern lights. Some sources are designed to emit electromagnetic fields that can non-deliberately interact with other systems. Examples of this include Wi-Fi devices, baby monitors, and cordless telephones. Emitting sources can also be less innocent. Electromagnetic warfare, such as communication jamming devices, has become a modern societal concern. All of these factors contribute to the design of equipment for transmission of electrical signals for communication and other applications.

Not only can electromagnetic interference pass into electrical circuits and cause disruption, known as ingress [4], but electrical circuits can leak out signal too, known as egress [5]. Egress can have its own undesirable affects, including diminishing signal quality as well as causing interference to other surrounding devices. It furthermore may be possible for persons to collect potentially damaging information from leaked signals.

For these reasons, it is very important to prevent disruption of signal both from entering a circuit as well as from leaking out of a circuit. The best method currently implemented to isolate signals is by using electromagnetic shielding. Electromagnetic
shielding is typically a conductive and/or magnetic material enclosing the protected signal. Shielding can come in a multitude of forms: from foils to conductive paints.

2.3 *Electromagnetic Shielding*

The shielding of electromagnetic interference is critical for operation and reliability of electronics and the rising prevalence of radio frequency radiation sources \[6\]. A material can shield radiation via several mechanisms giving an overall shielding effectiveness, SE, as seen in the equation below \[6\].

\[
SE \text{ (dB)} = 10 \log \frac{P_{in}}{P_{out}} = A_{dB} + R_{dB} + B_{dB}
\]

Where,

\[
A = \text{Attenuation due to absorption (dB)}
\]

\[
R = \text{Loss due to reflection (dB)}
\]

\[
B = \text{Re-reflection correction (dB)}
\]

\[
P_{in} = \text{Incident Power}
\]

\[
P_{out} = \text{Power transmitted through material}
\]

The primary mechanism employed by current EMI shields is reflection. For a shield to reflect radiation, the shielding material must have mobile charge carriers, either electrons or electron vacancies \[6\]. Metals are the most common type of electromagnetic shielding for this reason; they possess free electrons which reflect radiation \[6\]. In addition, high conductivity, low resistivity materials with charge mobility can create what
is known as a Faraday cage to shield electromagnetic fields or even electric discharges, such as lightning [8]. A Faraday cage/shield allows for the flow of electrical charge to flow on and along the shield but not through such an enclosure. The flow of electrical charge within the conducting material allows for a distribution of charges such that it cancels the effect of the electromagnetic field on the interior of the shield. Metals are the often chosen conducting material for such shielding applications however metals unfortunately tend to be bulky and heavy. Metal coatings created by electroplating or vacuum deposition are less bulky but are prone to wear and have little scratch resistance [6].

Materials can also shield by absorbing radiation. An absorbing material typically has electric and/or magnetic dipoles. These dipoles interact with the electromagnetic fields within the radiation thereby absorbing it [6]. Materials with high magnetic permeability, such as supermalloy or mumetal, are excellent for absorption [6]. This can be further enhanced via use of a multilayer of magnetic films to reduce the number of magnetic domain walls [6].

Typically, the shielding reflection loss increases with increasing frequency and absorption loss decreases with increasing frequency [6].

Finally, a material can shield by reflecting between or across multiple interfaces [6] as shown in Figure 2.2 [9]. This is where composites and nano-materials become an interesting and viable shielding option. Many times, composites and nano-materials contain constituents that have exceeding large surface areas which provide significant interface regions which can partially-absorb and dissipate radiation [9]. Using materials
with high surface area filler not only can help shield electronics but also potentially provide significant weight savings when compared to metal shielding counterparts.

![Multiple Reflection Mechanism](image)

**Figure 2.2:** Multiple Reflection Mechanism (Reproduced with Permission of 2009 Elsevier) [9].

A metric sometimes used to characterize a material’s response to an impending field is known as the skin depth or \( \delta \). It is the depth within the material at which the field has decreased (regardless of the shielding mechanism) by a factor of \( 1/e \) of the incident value. The skin depth relates to the conductivity of the material, \( \sigma \), the incident frequency, \( f \), and the material’s permeability, \( \mu \) [6, 10, 11].

\[
\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}
\]

Physically speaking, minimizing the skin depth of the shield is desired so that less shielding thickness is required. This reduces device bulk, can decrease weight, and allows for greater mobility. To best achieve adequate shielding at low skin depths across a
broadband of frequencies the material must possess high permeability and/or high conductivity.

2.3.1 Skin Effect Mechanisms

This effect, known as the skin effect, is caused by the external changing/alternating electromagnetic field inducing an alternating current within the outer conductor. This alternating current produces a subsequent magnetic field. When the intensity of the current changes (as is the case with alternating current), the resulting magnetic field changes. Changes in the magnetic field cause a back electromotive force due to Faraday’s law of induction. This law states that when a current/electromotive force is induced it flows in the equal and opposite direction as the time rate of change of the magnetic flux, also known as Lenz’s law [13]:

\[
\varepsilon = - \frac{\partial \Phi}{\partial t}
\]

This means that eddy currents force electrons, i.e. current, to flow at the “skin” of the conductor while reducing current flow towards the interior as seen in Figure 2.3 below. In the case of shielding, the skin depth is a measure of the thickness required to attenuate the impinging wave thereby reducing the induced current.
Figure 2.3: Schematic of the Skin Effect in a Sample.

As seen in the skin depth equation, the material thickness required to shield is dependent on the frequency, electrical permeability and electrical conductivity; less thickness is required for higher conductivity materials. For non-magnetic materials, in the case of nanoscale multi-walled carbon nanotube material, the permeability is taken as unity ($\mu = 1$) [12]. The skin depth is therefore dependent on the frequency and material conductivity for nonmagnetic materials.

2.3.2 Shielding-Conductor Relationship

Much of the purpose of electromagnetic shielding is to achieve electrical isolation. This function is two-fold. Shielding can serve the purpose of improved safety but also for protecting internal electrical signals (which also in turn ensures safety). For instance,
lightning strike protection engineering within aircraft fuselages serve the purpose of safeguarding those on board but also to shield the complex system of internal electronics.

In many cases, internal electrical signals are sent within circuitry/metal conductors. A shield encapsulates the system such that the conductor and therefore electrical signals are protected from external fields.

To make assessments of the performance of electromagnetic shielding in such instances, it is necessary to consider the internal conduction of electrical signals as well as any interactions between the shield and the conductor, as is the case in a coaxial geometry. When evaluating shielding, if the center conductor is not functioning properly it could be falsely attributed to shielding performance, for better or worse.

2.4  **Principals of Electrical Conductivity**

Electrical conductivity is a highly desirable property for both shielding (as seen in the skin depth equation) and in conducting signal in coaxial systems.

The amount of power dissipated in which there is resistance involved can be expressed as the combination of Joule’s law and Ohm’s law:

\[ P = VI = I^2R \]

Where P is the power expressed in watts, V is the voltage in volts, I is the current in amps, and R is the resistance in ohms. Ideally the power lost in any circuit would be minimized and therefore the resistance low. Resistance, R, varies as:

\[ R = \frac{l}{\sigma A} \]
Where l is the length of the resistor or material under test, A is the cross-sectional area, and σ is the material conductivity. Conductivity and resistivity are inversely related.

Resistivity/conductivity is based on several factors. It is a material microstructure sensitive property [16]. Conductivity is governed by two main aspects, the number of charge carriers, electrons or holes, in the material (concentration), n, and the charge mobility, μ. Q is the constant for the charge; in the case of the electron charge approximately 1.6 x 10\(^{-19}\) coulombs.

\[
\sigma = nq\mu
\]

The charge mobility represents the ease of movement for the charge carrier, or electrons. Electrons are reflected by atoms or defects and can take rather irregular paths through conductive mediums. This is why conductivity is sensitive to microstructure. If dislocations or grain boundaries are present, electrons present cannot move as easily and conductivity is reduced.

The principal applies to traditional metals such as silver or copper. In the case of copper, conductivity/resistivity is greatly influenced by grain boundaries. With increasing number of grain boundaries, the resistivity of copper wires increases. The resistivity of such wires, y, varies non linearly as a function of the number of boundaries, x, as [17]:

\[
y (x) = 1.86 \times 10^{-8} e^{-0.90/x}
\]

Dislocations and vacant sites also increase the resistivity of copper wires linearly [17]. Overall with their available electrons and crystal lattice structure allowing for high
electron mobility, limited by their number of grain boundaries, metals have high electrical conductivity.

For the case of carbon nanotubes, nano-scale conductivity measurements show exceedingly high values (which will be discussed in more detail later). This is because using atomic force microscopy and four-point resistivity measurements typically only involves investigating a single or a small bundle of aligned nanotubes.

While for large macro-scale samples that involve many, many nanotubes and therefore junctions (as there are size limitations of growing capabilities of carbon nanotubes), these measurements often show less ideal values. Conductivity is much more complex in bulk scale systems of disordered nanotubes.

Electron transport in larger scale disordered carbon nanotube samples is diffusive, involves many electron-scattering occurrences and therefore reduced mean free paths [18, 19]. Li et al. observed that tunneling resistance plays a dominant role in the electrical conductivity of composites and the maximum tunneling distance was found to 1.8 mm [104]. Carrier mobility is consequently reduced. Transport of electrons in carbon nanotube networks is dominated by the resistance at network junctions which requires electron tunneling, with resistance varying as a function of junction length and thinner tube inner circumference [20, 21].
Nirmalrad et al. showed the resistance associated with electron transport pathways for imperfect junctions shown in Figure 2.4 [21]. When individual tubes are discontinuous and not lined up to one another, suddenly the resistance associated with such transport increases. The resistance for the total network increases [21]. Bulk amorphous carbon nanotube materials like the ones implemented in this research, have millions to billions of imperfect junctions if not more. For this reason, the conductivities

**Figure 2.4:** Atomic Force Microscopy Results on Pristine Sparse Networks. (a) Current Map of a Nanotube Bundle which is Intersected by an Individual Tube. (b) Local Resistance Analysis Through the Bundle and Individual Tube Depicted as Pathway 1 and 2 as Shown in the Schematic (c). (d) Current Map of Interconnected Tubes of Varying Diameter Showing the Formation of Junctions with Varying Resistances. (e) Local Resistance Analyzed Along the Individual Tube Connected to a Sparse Configuration of Nanotubes Highlighted as Pathway 1 and 2 as Shown in the Schematic in (f) (Reproduced with Permission of American Chemical Society 2009) [21].
of such materials will be far inferior to that of single nanotubes or small bundles and will be restricted by the sheer volume and complexity of junctions.

2.5 The Shortcomings of Traditional Conductors/Shields

The industry standard for shielding, circuitry, and conductors is typically metal and is often specifically copper due to its high conductivity, accessibility, and cost. Metal however has its own drawbacks in these applications.

The largest drawback of metal is that it is heavy. Weight in industries like the aircraft, transportation, and aerospace industries is costly. These same industries depend heavily on high quality shielding and proper electrical communication.

In the aviation industry, every weight savings possibility is considered. Japan Airlines has even gone so far as to cut the weight of each piece of small cutlery on international flights by an average of .07 ounces [14]. This seems extreme until you bear in mind that a company like former Northwest Airlines saved $440,000 a year for every 25 pounds they removed [14] from all flights.

Not only does weight affect expenses but it can largely affect logistics and range. With maximum fuel volume on board most aircraft, reducing payload by cutting cable weight can increase flight distance. The other alternative is by cutting cable weight payload can be reconfigured and carrying capacity can be increased.

Secondly commercial conductors with standard metal shielding have many documented issues of electromagnetic interference. Mishaps have transpired in vehicles such as the F-16 in its flight controls, by flying in the vicinity of a Voice of America radio
transmitter [15], to NASA missions, such as in the Spacelab and the Apollo telescope mount within preliminary tests of the telemetry and measuring system wires. This could have rendered data transmission to ground useless [15]. Failure of traditional shielding has happened in many common non-aerospace devices as well. Faults have occurred in various every-day systems. Early anti-lock braking systems in both automobiles and aircraft have had accidents caused by electromagnetic interference due to improper shielding of the control system. Initially the resolution was to provide a manual switch to resume normal breaking when electromagnetic interference yielded the system inoperable [15]. Heart monitors, defibrillators, and wheelchairs, all have had reported cases of traditional shielding causing electromagnetic interference anomalies as well [15].

Most of the detrimental cases of cable shielding malfunctions tend to be due to ingress of external power. Egress of data and signals is also quite possible. While maybe not as physically destructive, egress of signal due to poor quality shields could potentially allow information to pass to the wrong hands, especially with the exorbitant amount of portable electronics in today’s world. It can cause power to diminish and in some cases not properly reach its source.

Furthermore, an underlying cause of such shielding breakdowns, other than potential fundamental design flaws, may be mechanical fatigue.

Fatigue is the failure of material or lowering of strength due to repetitive stress which may be above, or many times, below the yield strength [16]. Fatigue can even be electrical in nature, sometimes seen in materials such as ferroelectric thin films, which can eventually cause an inability of a material to show electrical property changes in response
to applied electric fields [16, 22]. Generally, anytime a component is subjected to electrical, mechanical, thermal, or magnetic cyclic forces over long periods of time, fatigue may be cause for concern [16]. In fact, in aircraft alone, fatigue is responsible for 61% of all componentry failures [23]. It is essential that shielding of circuitry and sensitive systems perform despite cyclic stresses that it may experience because of occurrences like installation procedures, or thermal fluctuations particularly in aerospace applications.

2.6 Carbon Nano-Material Alternatives

Metals are dense (which drives up costs and affects logistics), have many documented cases of electromagnetic interference, and many times fail due to mechanical fatigue. Because of this carbon nanomaterials have gained momentum as a potential replacement of metals as an electromagnetic shield and even as a conductor. Carbon nanotube and nanofiber structures have garnered particular interest because of their superb electrical properties, high strength, and fatigue resistance.

2.6.1 Conductivity of Carbon Nanotubes

On the molecular level, carbon nanotubes are essentially nanoscale cylinders of graphene sheets. Carbon atoms are bonded together as an sp2 hybridized covalent bond. In an sp2 hybridization, the 2s and two 2p orbitals hybridize and form three sp2 bonds which enables the formation of σ bonds. In this trigonal symmetry, the fourth electron in the p orbital is not a part of the sp2 hybridization, which leads to it forming a π bond in the perpendicular plane. When these π bonds are oriented, ballistic electron transport is supported along the length of the nanotube. This leads to high mean free paths and exceptionally large conductivities. The problem is for using carbon nanotubes for bulk materials, nanotubes have finite lengths.
For carbon, conductivity can depend on the nanostructure/morphology. Carbon nanotubes of the metallic variety, typically the arm-chair configuration, transport electrons ballistically and without scattering. They can carry high currents with essentially no heating along the nanotube length [24, 25]. Reported values for electrical conductivity of single carbon nanotubes come close to the theoretical value of $7.7 \times 10^6$ S/m [26], which exceeds that of copper at $5.7 \times 10^7$ S/m [26] and current density measures as high as $10^9$ A/cm$^2$ [27]. Carbon nanotube ropes have measured resistivity at 300 K of $10^{-4}$ Ohms* cm$^2$ [6]. Conduction of carbon nanotubes at room temperature on the macro-scale is limited in most part due to the junctions between the nanotubes themselves. These properties and others coupled with their low density, make carbon nanotube based materials an intriguing prospect as a metal alternative for conducting and shielding applications.

2.6.1.1 Frequency Dependent Conductivity of Carbon Nanotubes

For the purposes of sending signals properly along a transmission line or other circuitry, it is vital that a conductor material maintains its conductivity over a broadband of frequencies. This aspect is also of crucial importance to protect against interference from a comprehensive range of sources. Carbon nanotube materials, interestingly, do not conduct the same across all frequencies [28-33].

Depending on the degree of ordering of the carbon nanotubes in a macro-sample, the alternating current conductivity of carbon nanotube films increases with increasing frequency [34]. In single walled carbon nanotube semi-conducting network assemblies, conductivity grows up to 400% of its direct current conductivity at 120 GHz, as seen in the figure below for single walled carbon nanotubes [28].
Figure 2.5: Conductivity versus Frequency for Single Walled Carbon Nanotube Samples and Models. (Reproduced with Permission under the Creative Commons License) [28].

With such large signal carrying capability, even increasing at higher frequencies, nanoscale carbon-based components could be quite promising. Not only is the trait conceivably beneficial as a center conductor but also as a shield within electromagnetic fields. Resistivity and conductivity are a measure of how strongly a material transfers or opposes the flow of electrical current, respectively. Given that electric fields cause current to flow, and proper shields block fields by channeling this electrical flow along and around the shield but not through, high conductivity materials are a customary choice for efficient shields. This could be held true for carbon nanotube based material.
2.6.1.2 **Morphology Dependent Conductivity of Carbon Nanotubes**

Another major factor that affects material conductivity of carbon nanotubes is their structure or chirality. There are three main chiralities of carbon nanotubes. They are, zig-zag, arm-chair and chiral. These differences in wrapping patterns of the cylindrical tubes result in either a metallic or semi-conducting state of the nanotubes [35]. This is because of the periodic boundary conditions enforced on the electron wave pattern within quantized states which are dependent upon the nanotube structure. This means that how electrons are conducted within nanotubes is in large part a result of how much the tubes twist, i.e., their chirality [36].

Whether carbon nanotubes are primarily metallic, semi-conducting, or some mixture there-of has large macro scale impacts on conductivity [28, 35]. This is depicted in Figure 2.5; metallic carbon nanotubes clearly have higher conductivity and therefore signal carrying capability across the tested frequencies compared to the semi-conducting nanotubes. Both had significantly higher conductivity compared to the unsorted samples. The structure, alignment and sorting of carbon nanotubes plays a large role in the macro scale conductivity of bulk carbon nanotube materials.

2.6.2 **Carbon Nano-Materials for Shielding**

Of course, low density nanoscale carbon material shields or conductors are nothing entirely new. Carbon nano-fibers and carbon nanotubes have been widely investigated as a general electromagnetic shield. Nano-fibers and nanotubes are many times used as constituent for nano based composites [37-40]. Resin or polymer systems provide structure and shape to fiber and nano-reinforcements, while simultaneously conductive reinforcements deliver shielding.
A common shielding composite combination is of carbon reinforcement in polymer or resin matrix. As an electromagnetic shield, carbon fillers in polymer can serve a more unique purpose. Most polymers are electrically insulating, which makes them transparent to electromagnetic waves. When conductive nanoparticles are scattered within at certain concentrations the total reflection is limited but the shielding improves due to the induced absorption and dissipation of radiation in the conductive particles.

The problem with using polymers and certain resins is the lack of flexibility and conformity they supply, which is critical in electromagnetic shielding. In recent years, companies, such as Nanosperse LLC (using carbon nanofibers generated by Applied Science Inc.), have developed carbon nanotube materials in sheets or tape form. While much of these manufacturing processes are proprietary, materials like these are commonly made using a similar process to that of paper production. They use cellulose as a binder, making a composite type paper.

Using this method of fabrication for carbon nanotube sheets allows for greater mass production proficiency [43]. In addition, carbon nanotubes and nanofibers in this form maintain an ability to shield electromagnetic fields. Fugetsu et al. were able to fabricate large sheets on CNT/cellulose paper with a thickness of 0.45 mm and a width of 50 cm on a mass production line. These same sheets, with a weight fraction of dispersed nanotubes of 8.32%, had a peak shielding effectiveness value at 35 GHz of 40 dB [43]. Interestingly, the absorption efficiency (as opposed to reflection or transmission) increased with increasing frequency [43]. Setting itself apart from carbon black is that carbon nanotube/cellulose composites have a strong tendency for the nanotubes to entwine themselves around cellulose fibers which may increase entanglement.
Carbon nanotubes and associated nano-enabled composite products provide a highly promising novel option for electromagnetic shields and even in some cases as a centerline conductor. Therefore creating accurate methods to assess signal properties and shielding effectiveness of these materials in applicable geometries will be vital moving forward.
CHAPTER 3
ELECTROMAGNETIC SHIELDING TEST MEASUREMENTS – A REVIEW

Electromagnetic shielding materials have been around for quite some time and there are already a variety of established techniques for determining their performance. Most of these approaches are customary for evaluating metals and/or planar geometries. There are also several ways in which more complex geometries can be investigated.

3.1 Planar Measurements

Planar techniques require material samples fitted to certain two-dimensional geometries to mount within designed sample holders. A plane wave is impinged on the sample normal to the surface and corresponding shielding measurements are derived.

Most planar measurement techniques utilize the same set of governing equations, which are derived from the general wave equation:

\[ \phi_L(x) = a_1 e^{ikx} + b_1 e^{-ikx} \]

\[ \phi_R(x) = a_2 e^{ikx} + b_2 e^{-ikx} \]

Where \( k \) represents the wave number/vector

\[ k = \sqrt{2mE/h^2} \]
The first equation is for the wave headed towards the sample or to the left of the sample and the second is for that of the wave to the right of the sample. The term with coefficient $a_1$ represents the incoming wave while the term with coefficient $b_1$ represents the reflecting wave from the surface. The $b_2$ term is the outgoing wave from the sample and the $a_2$ term would be any wave being impinged on the backside of the sample.

![Wave Impingement Schematic](image)

**Figure 3.1:** Wave Impingement Schematic

Using these equations, a scattering matrix can be solved for such that,

$$\varphi_{out} = [S] \varphi_{in}$$

Where the S matrix, or scattering matrix, can be solved for [44]. In the case of a two-port system:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

The scattering matrix in and of itself is quite useful. It gives engineers quick insight to the transmittance and reflectance of a device or sample. Each scattering parameter is a unit-less complex value, which in this case the magnitude is expressed in the logarithmic term of decibels. For a two-port system, S11 is the input voltage reflection coefficient, S21
is the forward voltage gain, S22 is the output voltage reflection coefficient and S12 is the reverse voltage gain. The scattering matrix can be used to evaluate full systems (such as a transmission line or antenna) or the properties of a single material sample. To gather more information with regards to a sample material’s ability to shield, the terms of Schelkunoff decomposition can be calculated. The elementary coefficient (as the solution $|\rho| \leq 1$) can be determined as such below [45]:

$$
\rho_1 = \chi \pm \sqrt{\chi^2 - 1}
$$

Where,

$$
\chi = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}}
$$

The wave propagation term can be solved for as:

$$
e^{-\gamma t} = \frac{S_{11} + S_{21} - \rho_1}{1 - (S_{11} + S_{21})\rho_1}
$$

Using these terms, the shielding components can be deduced [45].

$$
A = -20\log_{10}|e^{-\gamma t}|
$$

$$
R = -20\log_{10}|1 - \rho_1^2|
$$

$$
B = 20\log_{10}|1 - e^{-\gamma t}\rho_1^2|
$$

Where A is the absorption loss of the sample, R is the reflection loss, and B is the multiple internal reflections component, all of which are expressed in decibels and sum to the total shielding effectiveness.
\[ SE = A + R + B \]

3.1.1 Wave Guide Measurements

There are many ways in which to make waveguide shielding effectiveness measurements. The primary waveguide geometry techniques are coaxial, cylindrical, and rectangular waveguide measurements. A waveguide is essentially a hollow metal pipe used to guide far field electromagnetic waves within certain frequencies and modes depending on the design of the fixture. The structure diameter must be half the wavelength or larger for the radiation to correctly propagate. The typically planar and isotropic material is inserted into the fixture and the incident and transmitted power is calibrated against reference samples (and many times no sample) and used to calculate the shielding effectiveness.

![Schematic of Example Waveguide](image)

**Figure 3.2:** Schematic of Example Waveguide (Reproduced with Permission of Royal Society of Chemistry) [46].
ASTM standard D4935 outlines the procedure for measuring the electromagnetic shielding effectiveness for planar materials in far field, normal incidence, plane wave circumstances [47]. The sample holder has an enlarged coaxial geometry with tapered sections and matching notched groves. A pair of flanges in the center of the structure hold the disc shaped test specimen and nylon screws hold the symmetric holder together. The results are valid at a frequency range of 30 MHz to 1.5 GHz [47]. In addition, the test samples and reference specimen must be shaped to perfectly fit the sample holder. In particular, the sample thickness has a large effect on the accuracy of the measurement. For repeatability, the difference between the test and reference specimen must have a difference in average thickness 25 μm or less and the thickness variation within and between samples must be less than 5% on average [47]. Test specimens can be homogenous or inhomogeneous, single layer or laminate but, of course measurements of inhomogeneous samples are dependent upon orientation and sample geometry. Another similar setup uses a coaxial geometry holder with a continuous conductor and planar annular sample geometries. It relies on the same equations (see section 3.1) to calculate the shielding effectiveness of the sample [48].

3.1.2 Focused Beam

The focused beam measurement method was largely established by John W. Schultz at the Georgia Tech Research Institute. Radiation is created using a feed antenna. A dielectric lens focuses the radiation on a planar material sample. On the opposing side of the sample is a reciprocal lens and antenna. The transmission and reflectance of energy from the sample is measured on either side of the material and plane wave interaction scattering parameters are calculated [49]. As with most measurement systems, calibration
with known standards and/or air is required for accurate results. One large benefit on using a focused beam measurement system is that many anisotropic materials may be evaluated and polarizations and phase can often be calculated [49]. Conversely, large planar samples are required and error largely fluctuates as a function of the thickness compared to the wavelength [49].

**Figure 3.3:** Focused Beam Schematic.

**Figure 3.4:** Focused Beam Principal (Reproduced with Permission of 2009 IEEE) [50].
3.1.3 Enclosure Measurements

Enclosure measurements can be made in several environments (these will be described in further detail in the following section). A sealed shielded box lined with highly absorbing material and a large aperture on one side is placed within a field, often an open area test site or reverberation chamber [51]. Conversely an enclosure with two segments and internal source can be used as well. The power inside the enclosure with the planar sample in place is compared to the power inside the enclosure with the empty aperture [51, 52]. Power can also be radiated from inside the box and measured exterior to the enclosure, in a reverberation or an anechoic chamber (both environments ensure no external noise is present) [53].

This method is particularly useful for comparison purposes of materials. Getting adequate electrical connection between the sample and the enclosure can often prove difficult. With electrical contact being difficult to achieve, possible interactions between shield and enclosure, and varying enclosure parameters, there is poor correlation between laboratories using this test measurement method [51, 54]. In addition, with a frequency range of only 500 MHz, this technique certainly has its limitations [51].
Figure 3.5: Enclosure Method Test Set-Up (Reproduced with Permission from John Wiley and Sons) [51].

3.2 **Co-axial Geometry Measurements**

Planar measurement methods, while useful, do not take into account complex geometries relevant to many actual applications. Not all angles of incidence are normal to the test article in real scenarios. If all electronics could simply be shielded by an infinite plane of solid metal, engineering would be a lot easier. However, in practical applications, three dimensional bodies require the use of complex shields that involve slits, apertures, joints, seams etc. These all have strong effects on electromagnetic interference [55, 56]. There are several measurements methods that can allow for testing of a non-planar, coaxial geometry of a shield and conductor.

Open area test sites, anechoic chambers, and reverberation chambers are often considered testing environments and can accommodate many different geometries and set-
ups while TEM cells and triaxial cells are cells and (depending on their size) can be considered bench-top test methods.

### 3.2.1 Open Area Test Sites

An open area test site, sometime refer to as OATS, is simply that. The importance of an open area test site is to more closely mimic real-world scenarios. Locations are typically in isolated areas as to reduce ambient noise [57]. This measurement scenario is quite practical because electromagnetic interference, should it occur, does not typically occur in silent or shielded rooms but rather in environments where propagation can be wide and random.

Many different shield geometries can be examined using open area test sites however testing can be arduous and complex. Enclosures/shielded boxes can be used in conjunction to test planar material samples or whole equipment can be tested with OATS. In addition, structures and coaxial geometries can be tested by either comparing back to field mapping data, sensors, or the same unshielded conductors [57]. Admittance and emission can both be tested.

Open area test sites can be expensive and time consuming to use. Their repeatability or accuracy can vary with weather, surrounding structures, and the quality of the ground plane [57].
Figure 3.6: Fundamental Open Area Test Site Arrangement (Test Articles or Enclosure Would be Used in Place or in Conjunction with the Receiving Dipole) (Reproduced with Permission of 1985 IEEE) [58].

3.2.2 Anechoic Chamber Testing

An anechoic chamber is an echo free or non-reflective chamber. The environment is isolated from outside noise and can be used for either susceptibility (electromagnetic energy entering a device from the environment) or emissions (electromagnetic energy leaving a device to the surrounding environment) testing. The chamber has fully lined surfaces of radiation absorbing material, otherwise known as R.A.M., in carefully designed patterns, typically pyramids/cones. The dimensions of the R.A.M. correspond to limits in the test frequencies as well as the test volume available. A screened room is also necessary to ensure measurements taken are accurate and unobstructed.
An anechoic chamber can also be used in conjunction with other test methods such as with a T.E.M. cell (description to follow) or an enclosure. Additionally, they can be used to evaluate large or unusually shaped test items.

![Diagram of anechoic chamber setup](image_url)

**Figure 3.7:** Anechoic Chamber Example Test Set-Up (Reproduced with Permission under Creative Commons Attribution) [59].

### 3.2.3 TEM Cell

A T.E.M. cell (short for Transverse Electromagnetic cell) or a G.T.E.M. cell, if operating in the gigahertz range, can be used to measure either emission or susceptibility within a field. It can either be fully conductively enclosed and use radiation absorbing material at one end or can be an open wire array and used in combination with an open area test site or anechoic chamber.

T.E.M. cells of the enclosure sort are traditionally long rectangular pyramids in shape. A signal generator and antenna are used at one end and a load or R.A.M. is used at the other with the equipment under test in between. This test method can be sensitive to the
orientation of the sample. In addition, there is a trade-off between the possible size of the test article (and therefore size of the TEM cell itself) and the reliable experimental frequency range [58].

![TEM Cell Example Test Set-Up](image)

**Figure 3.8:** TEM Cell Example Test Set-Up (Reproduced with Permission of 1985 IEEE) [58].

### 3.2.4 Triaxial Cells

Triaxial, test set-ups produce a different measurement metric. This method (and other analogous methods, quindraxial etc.), yield a shield’s surface transfer impedance. Surface transfer impedance is defined as [60]:

\[
Z_T = \frac{1}{I_0} \frac{dV}{dz} \bigg|_{l=0}
\]
That is the voltage drop on the inside of the shield over the length of the measured system divided by the current flowing on the outer surface of the shield (or surface closest to impinging field) [60].

The set-up is entitled triaxial cell since the fixture forms a triaxial geometry between its outer cylinder, the shield of the cable, and the centerline conductor. The fixture essentially forms two coupled transmission line systems [61]. Depending on whether emissions or immunity is being evaluated the system is short circuited in various configurations and the electromagnetic coupling or leakage is measured [61]. Highly complex calculations yield the shield’s surface transfer impedance.

This method is popular due to availability and size of the test fixture however the frequency is highly limited as the wavelength of interest approaches the radial dimension of the outer tube [62]. In addition, propagation of the impinging field is only in the transverse direction.

**Figure 3.9:** Example Triaxial Cell Schematic (Reproduced with Permission of 1998 IEEE) [63].
3.2.5  Reverberation Chambers

Traditionally reverberation chambers are used to test shielding efficiency across a wide band of frequencies; in particular, they are able to achieve frequencies as high as 18 GHz like in this study and others [64-66]. This is higher than many other discussed methods. For example, triaxial cell measurements have an upper test frequency between 100 MHz to 1 GHz [61, 62, 67].

Injection probes or more typically a horn or antenna can be used to impose radiation on the equipment under test or upon a shielded enclosure. A carefully designed paddle spins to alter boundary conditions and ensures a uniform field is achieved [66, 68]. One of the most appealing benefits to using a reverberation chamber is the way in which it represents complex real life environments; the excited field comes from any direction (i.e. at all aspect angles) with any possible polarization or phase [66,69]. In addition, results are robust and repeatable [66, 69, 70].

Reverberation chambers, like the one utilized in this study, are quite practical for a wide variety of tests. The advantages for using such a test method over other possible methods for assessing electromagnetic shielding include: an electrical isolation from or to the external environment, accessibility, an ability to generate high level fields efficiently over large test volumes, a broad coverage of frequency, cost effectiveness, potential to test both radiated susceptibility and emission testing with minor instrument changes, and no requirement of physical changes to the device under test [71].
3.2.5.1 **Bare Cable Comparison**

The major metric used to evaluate electromagnetic shielding capability within reverberation chambers is shielding effectiveness. This is measured in reverberation chamber tests (and several other setups) with a coaxial system as: ten times the log ratio of received power on the bare wire (the conductor without the shield) to the power received on the shielded coaxial conductor [74-77]. Conventionally and more generally speaking, shielding effectiveness can also be measured as ten times the log ratio of the incident power, as measured by a reference antenna in the reverberation chamber, to the power transmitted to, in this case, the center conductor or the coaxial cable [1, 66, 75, 78, 79].

In a completely novel coaxial system, one that utilizes non-traditional materials, neither of these definitions are practical. In the case of the naked cable, due to impedance
mismatches within the unshielded conductor in the radiated field of the reverberation chamber, standing waves can form. The cable under test is assumed to be impedance matched to its source (in this study, a 50 Ω load), however when the shield is removed like on a bare cable measurement, this is no longer the case [75]. The coupling power from an infiltrating field to the naked cable can superimpose due to reflections off the mismatched load. This can cause pattern effects or standing waves and errors in measurements [75]. Also, although coaxial systems typically designed to be matched to say a 50 Ω load, this doesn’t mean the impedance is a perfect 50 Ω across the entire operable frequency range (especially without a shield). This can be seen in later cable characterizations in section 4.1.1.

3.2.5.2 Reference Antenna Comparison

As mentioned, the other often implemented method to measure shielding effectiveness compares the power from a receiving antenna (in this study a log-periodic dipole array) to the power received on the shielded coaxial system [70].

\[ SE = 10 \log \left( \frac{P_{Rx \, Antenna}}{P_{Shield \, Coax}} \right) \quad [70] \]

The problem with this method is that it assumes the behavior of the center line conductor to be identical to that of a receiving antenna, and everything else is attributed to shielding. Receiving antennas are devices specifically designed to essentially sense and collect power from a field, so naturally they should produce higher signals than a simple carbon nanotube yarn or copper bare wire. When the centerline conductor is no longer a material like highly conductive copper, the assumption of the conductor behaving like a monopole antenna in a field may no longer hold true. Even in the case of a naked/unshielded silver or copper
center conductor, evidence from this research suggests the received power does not perfectly match the power received on the receiving antenna. In the Figure below, the power received on a sixty-inch naked/baseline copper conductor and carbon nanotube yarn conductor is compared to the receiving antenna for the same sweep within the reverberation chamber. In some areas, the difference of the carbon nanotube base baseline and receiving antenna is over 50 dBm (or the case of the baseline silver/copper conductor compared to the antenna, over 20 dB off), which using this measurement method gets falsely ascribed to the shielding effectiveness of the applied shield. This occurs, for instance with a carbon nanotube yarn conductor, because particularly without the shield, the system is losing more power than it is gaining (the conductor either has ohmic losses or is radiating out). It has been established that without a shield, a cable is not necessarily impedance matched across the whole range of operating frequencies. In this case, it appears with the high impedance not all the signal is making it to the load. Any additional power coupled into the system from the external field will likely be delivered to the load. In situations such as this, an alteration of 50 dB in shielding effectiveness can mean the difference in passing many applications’ shielding standards.
Figure 3.11: Received Power Comparison in Reverberation Chamber for Receiving Antenna, Baseline Naked Copper Conductor, and Baseline Naked Carbon Nanotube Conductor.

While reverberation chambers are a good choice for shielding assessments, the measurements systems employed within them needs improvement. In addition, testing in other environments, such as an anechoic chamber, may be feasible, but the same hindering principals would complicate those measurements as well.

3.3 Co-axial Geometry Measurements of Novel Materials

Several studies have explored the use of novel materials, mainly carbon nanotechnology, as a shield and conductor within applicable coaxial geometries. These studies have used several experimental techniques to evaluate the capability of such innovative materials within coaxial systems.
The incentive to test and use such new systems is clear. Replacing the copper shield and center conductor with carbon nanotube materials within coaxial geometries stands to reduce the weight of cabling down to 7.3 g/m, which results in a weight savings of 80% [80].

Harvey investigated several different conductive carbon materials and more traditional materials for use as a shield, as well as carbon nanotube yarn produced by Nanocomp Inc. as a center conductor. The shields investigated included carbon nanofibers and nanotube based powders, tapes, and sheets. Shielding ability was only studied in a simple coaxial waveguide test using planar samples from 1 to 8 GHz. Substrates with a diameter of 3 cm were used.

Results showed carbon nanotubes in planar sheets had equivalent or exceeding shielding effectiveness to the traditional metallic over-braid shield at 4 GHz [81]. The shielding effectiveness of two layers of carbon nanotube sheets measured 52 dB compared to 50 dB for the commercial metallic over-braid [81]. The biggest difference is that for the same shielding area, the metallic over-braid is almost 90 times denser. The single carbon nanotube sheet shield is slightly more than 1% of the weight of the metal braid shield [81].

Harvey also constructed RG-316 coaxial cabling prototypes using Nanocomp Inc manufactured carbon nanotube yarn as a core conductor with carbon nanotube tape from the same manufacturer as the outer shield and examined insertion loss from 10 MHz to 10 GHz, as seen in Figure 3.12.
There was significantly more attenuation (loss) for the complete carbon nanotube sheet coaxial construction, roughly one hundred times more, which was attributed to poor conductivity as well as irregularities in the yarn. In addition, copper core samples with carbon nanotube sheet shielding also experienced more attenuation than copper core samples with the commercial metal braided shield, almost ten times more. The complete nanotech based prototype, however, was 69% lighter than a standard RG-316 cable [81].

Harvey likewise studied some aspects of mechanical ability which was the effect of crimp style on tensile strength. Crimp style, in this case either F or O style with a metallic plating (nickel, tin, gold, or brass), showed no effect on breaking strength. The breakage strength of crimped samples remained consistent with non-crimped materials [81]. The yarn manufacturer reports tensile strengths of 84 N, while the tests showed breakage for the crimped samples to be 78.69 N on average [81]. All of the samples failed far from grips due to yarn breakage, not pull out [81]. This is important since it displays that in mechanical tests for coaxial geometries, connectors/crimps are not influencing their tensile properties.
Harvey concludes that while higher frequency shielding with low to moderate rate data transmission may be a current utilization for such novel carbon nanotech based conductor and shields, the immediate use of high speed data transmission and power cabling are not there yet due to high attenuation losses [81]. On a separate note, carbon nanotech materials currently lack the ability to be perfectly assimilated into present infrastructure without incurring high retooling expenses. Overall improvement of conductivity is essential to being fully utilized in the existing market [81].

This study, while valuable, illustrates the methodology currently employed to investigate novel conductor-shield systems. That is to evaluate each component individually. The planar shield is assessed at a narrow frequency band (1-8 GHz), which may not give a complete indication of how the actual cylindrical shield geometry will perform, especially within operating conditions or external fields outside of that range. A planar sheet will of course have different effectiveness at different frequencies than an applied braid or helical wrap. This is due to the addition of apertures and portions of possible double layering. In addition, the conduction characteristics are evaluated (separately) in the coaxial form but this information is not used in conjunction with shielding abilities; the shield is simply considered as to how it prevents further attenuation of the signal. Lastly some mechanical tests are done but not for the purpose of how it relates to the conduction or shielding effectiveness.

Jarosz has conducted several different studies relating to the use of carbon nanotubes in coaxial geometries [26, 80, 82].
Jarosz conducted an in-depth comprehensive review of all current and future prospective technology involving carbon nanotube wires and cables. The author cites that new materials may hold the appeal of reduced resistance, mass, and susceptibility to fatigue but questions how well they actually function in real systems.

To be utilized as cabling conductors, materials must be able to transmit electrical power or data signals with very little loss, usually requiring high material conductivity. High tensile strength and thermal load bearing capabilities are typically required for applications such as high-tension power transmission lines. Many times, electrical permittivity and magnetic susceptibility of cable shielding affects how well cabling can resist electromagnetic interference. In the case of carbon nanotubes, low resistivity, high tensile strength, high resistance to strain hardening, and broad environmental resistivity make it a potentially beneficial option for cabling conductors or shields [26].

The properties of carbon nanotubes can be quite deceptive. Often incredible traits seen on the nano or micro scale do not translate to large magnitude applications, as explained in Chapter 2.3. Bulk properties of carbon nanotubes are based upon both individual carbon nanotube properties as well as the total network composition. Properties such as tensile strength, electrical, and thermal conductivities have not yielded the same measurements in bulk carbon nanotubes and nanofiber materials, nor even in smaller close packed arrangements, as they have on the individual basis [26]. Major inherent constrictions, such as resistance to charge transport between separate carbon nanotubes and bundles, are inhibiting translation to larger volume characteristics [83-87]. Manipulation, such as doping, increased alignment, and densification can potentially advance nanotube networks and enhance mass material traits. With such innovations, reported conductivity
values of bulk carbon nanotube material have increased up to $1.3 \times 10^6$ S/m [26, 88]. While these values are still not quite as high as materials like copper, on a per mass basis it makes these materials actually viable; it also shows the vast possible improvements due to manipulation [26].

Nanocomp Inc produces predominately double and multi-walled carbon nanotube wire from a mechanical densification process using drawing dies. Jarosz et al. performed two studies using carbon nanotube material from this manufacturer and a treated version of the material to non-professionally alter commercial RG-58 and RG-402 cables. They removed and replaced the center conductor and shield to create carbon nanotube based coaxial cable prototypes [80, 82] as seen in Figure 3.13.

![Figure 3.13: Jarosz et al. Reconstructed Carbon Nanotube Coaxial Cable Compared to Commercial Copper Cable (Reproduced with Permission of 2012 ACS Publications) [80].](image)

The carbon nanotube shields were constructed using a cylindrical wrap system of varying wrap lengths. This, however, contrasts with standard cable manufacturing methods, which consists of helical wraps of shielding tape (which also provides flexibility). Prototype cables, consisted of carbon nanotubes shields with one-centimeter lengths wrapping around the cable once, two centimeters of shield wrapped around the whole length of the cable twice, so on and so forth (every centimeter yields one circumference
The shielding varied with wraps measuring 2 cm, 3 cm, 4 cm, and 6 cm. The shielding was wrapped around the dielectric and connector body and held in place with a tight spiral wrap of Teflon tape. Cables were disassembled and reassembled each test and maintained high conformity to the dielectric. The length of each cable, not including the Subminiature A connectors, was approximately 16 centimeters. All the attenuation and measurements made were compared on a per cable millimeter of length basis.

The as-received carbon nanotube based sheets measured an average conductivity of $7.6 \pm 0.4 \times 10^3$ $\text{S/m}$ [80]. Attenuation tests were performed from 150 kHz to 3 GHz. Attenuation is suspected to be largely compromised of resistive losses of the conductor with radiative losses contributing significantly less. Results showing attenuation due to shielding differences can be seen in Figure 3.14 section A. A skin effect behavior is confirmed of carbon nanotube based shields with attenuation showing a decreasing exponential trend as seen Figure 3.14 section c. Beyond about 4 skins depths, additional shielding thickness does not impact cable attenuation. Over 98% of current flows within the first three skin depths of the surface, even in the presence of impinging fields [89]. Jarosz et al. found the effective skin depth of the carbon nanotube sheet based to be about 100 $\mu$m [80].
Figure 3.14: a) Attenuation Comparison between Novel and Tradition RG-58 Cables. b) Wrap Diagram of Carbon Nanotube Shield. c) Attenuation Skin Depth Trends (Reproduced with Permission of 2012 ACS Publications) [80].

Reassembling the unique shorter cables did cause some inconsistencies unlike professionally constructed cables. Although not much deviation was seen between novel carbon nanotube sample reconstruction, the attenuation from the original RG-58 to the reassembled RG-58 was roughly double [80]. None of the cables were capable of meeting the criteria set by military specification MIL-C-17 with a max attenuation of 28 dB per 100 feet for RG-58 or 45 dB per 100 feet for RG-174 at 1 GHz [80]. Some potassium gold tetra-bromide treated carbon nanotube sheet material cables were much closer to meeting these
standards. With some possible improvements to carbon nanotubes processing as well as cable production it may be feasible to close this gap.

Jarosz points out that attenuation of cabling is not the only considerable response. Another potential benefit for using carbon nanotube materials in coaxial cables specifically is the mechanical properties and chemical stability. The Young’s modulus of carbon nanotube based composite conductive yarn, with potential coaxial conductor use, has been demonstrated at 120 GPa while still sustaining high electrical conductivity at $9 \times 10^4$ S/m [92]. In addition, carbon nanotube based conductor type yarns have been shown to be sufficiently flexure tolerant. A mechanically drawn carbon nanotube wire was compared to a commercial aerospace wire using a dynamic mechanical analyzer separated by four centimeters with a mobile clamp oscillating up and down one centimeter at 4 Hz. Four-point resistance measurements were taken in-situ. The carbon nanotube based sample showed no change in resistivity even after over 200,000 bend cycles. The commercial aerospace wire showed a rapid increase after only 8,000 cycles [26]. As mentioned earlier, the same yarns have the benefit of being resistant to corrosive environments [23, 26], and even have shown no long term trend of increasing resistivity after intense temperature cycling between 170 K and 220 K. In one experiment, little fluctuation of resistivity was seen with temperature; for densified carbon nanotube material, less than a 1% change was measured. In contrast, copper, which comprises a vast majority of commercial conductors, showed resistivity changes in excess of 200% over the same temperature range [26].

This study delves further into mechanical properties of incorporating carbon nanomaterials into coaxial systems. This set of work, however, only considers the effect of the shield on cable attenuation. A shield serves the purpose of more than simply retaining
signal around the conductor. This test method is not very informative as to the shielding ability of the outer conducting material; it simply tells how effectively signal is sent and retained. Using a testing method such as a reverberation chamber serves the purpose of studying conductor-shield systems in a random isotropic field without the need to reorient the sample [63, 66, 69, 70].

Jarosz highlights that using carbon nanotechnology in coaxial geometries is particularly promising for the future since great deals of improvements are continually being made. So far, there is no upper achievable limit set for the conductivity of bulk carbon nanotube materials [26]. With improvements available on densification, orientation, and doping, the incentive to replace traditional metal materials within shield and conductor systems is only becoming more attractive.

With the potential nanomaterials present for shielding and conductors, improved experimental measurement methods are necessary to confirm their performance and usability within coaxial geometries. While some shielding evaluations have been made on carbon nanotech shields and conductors, this work intends to bridge the gap so that novel or mechanically fatigued materials can be examined comprehensively as componentry in coaxial geometries both for their susceptibility and signal transmission.

### 3.4 Advanced Measurement Requirements

The objective of this work is to develop a method for measuring the shielding efficiency of nano-enabled functional conductor-shield geometries subject to mechanical fatigue. This necessitates an approach using a high electromagnetic frequency range, an analysis of the conductor and shield as a system, and incorporating the effects of: losses,
fatigue, and the electromagnetic field coupling of the center conductor. Measurements will incorporate conductor characterizations with and without the shield in place utilizing pre and post fatigue data by normalizing receiving baseline power values in a mode-stirred reverberation chamber according to the bare cable transmission. This novel technique will more accurately determine the shielding effectiveness of carbon nanoscale based shields in applied coaxial geometries of both metal and non-metal conductors across a broad frequency range. It will also accomplish the same for systems that have been mechanically fatigued in order to address the effect degradation has on signal carrying capability and electromagnetic shielding.

3.4.1 Broadband Frequency Range

Many test measurements have limited frequency bands due to measurement method size restrictions (anechoic chambers take up full rooms), signal resonances, and the appearance of higher order modes. Unlike many other studies, which assess the performance of planar shielding in a narrowband of frequencies, this work will aim to compare several three-dimensional shield materials across a frequency range up to 18 GHz. In addition, the electrical conduction performance of a center line conductor within the shield will be analyzed.

3.4.2 Independent Electromagnetic Shielding Measurements

Furthermore, the conductor and shield materials are studied as an interacting system. Many common communication circuits involve a central core conductor surrounded by a coaxial insulator and shield (for example coaxial transmission lines and conduit). Although it is often assumed that the coaxial geometry guarantees complete
separation of the conductor and shield, the materials can interact with one another, so it’s important to understand both the individual components and the system as a whole.

3.4.3 Effect of Electromagnetic Field Coupling in Nano-Material Conduction

One reason it is important to consider the system as a whole, especially within shielding effectiveness measurements, is that it is possible that due to conduction patterns of the center conductors, shielding values can possibly be inflated.

As a system, a coaxial cable is designed to be impedance matched to a load. A circuit is designed to deliver the proper power to a device or load. To deliver the maximum power, the source impedance must match the load impedance. Impedance is the measure of opposition of current when voltage is applied within a circuit. It is akin to resistance within Ohm’s law; however, impedance applies to alternating current. It incorporates both capacitance and inductance of the circuit and has a magnitude and phase. Impedance matching ensures that maximum power is delivered to the load/device and that reflection is minimized (which can cause interference). The characteristic impedance of a transmission line is the real portion of the ratio of the voltage and current of a signal traveling the line; it is independent of length. The standard design for many transmission lines is 50Ω (used since it limits power loss and reflection). The characteristic impedance of RG-316 coaxial cables, like the constructions used in this study, is 50Ω.

When shielding measurements are taken by comparing back to a baseline conductor (a stripped conductor with no shielding material), the system is no longer impedance matched. A bare conductor in a field connected to a 50Ω terminal load will see an induced current from field coupling and the lack of a shield. This can allow for reflections to
propagate. There is also the possibility of standing waves forming due to constructive/destructive wave interference of the signal on the bare cable and the waves of the imposing field [75]. It also likely means a portion of the signal being transmitted down the line can be lost, without the shield to retain it. In this study, the bare cables will be separately characterized and compared to the reverberation chamber results to understand the effects of the impedance mismatch within the electromagnetic field. Furthermore, those adjusted results will be used to calculate the actual shielding effectiveness of the complete system.

3.4.4 Effect of Fatigue on Conduction

Secondly fatigue of the center line conductor or of the shield, which many times results in breaks, can have a very similar effect on shielding measurements. Shielding effectiveness values can be grossly inflated when they are derived from comparing back to an intact center conductor baseline or compared back to a receiving antenna. Both methods assume any ingress is being received and transmitted on the center conductor; if the center conductor is broken or fractures, this will not be the case. Shielding effectiveness measurements of a system is dependent on the impedance of its constituents. Moreover, a system may no longer be impedance matched to the load if it is tested for shielding effectiveness with when fractures from fatigue have occurred. There does not appear to be a reliable method developed to gauge how well shielding performs once any mechanical damage has potentially occurred in this geometry.

3.4.5 Effect of Radiative Conduction Losses

One effect that is hard to account for that gets lumped in shielding measurements is the occurrence of radiative losses that happen without a shield. Without a shield over the
conductor within a reverberation chamber, the naked cable itself becomes a source of radiation [75]. This is seen in the comparison of the attenuation between a conductor with shield and one without. When a bare conductor has a signal running down it, in the middle of an empty chamber or field, part of that signal is lost or attenuated; placing a shield on the conductor actually helps retain that signal in many instances. Adding a shield and comparing to a naked cable, leads the newly preserved signal to appear like as ingress from an external field, when in fact the addition of the shield causes more retention of the internal power. The shielding effectiveness value gets falsely lowered as signal appears to be coupling.

3.4.6 Novel Measurement

With the lack of established methods that accurately capture the true nature of this complex and practical geometry and subsequent effects of mechanical degradation upon the materials, the question this research attempts to answer is:

How can electromagnetic shielding effectiveness be accurately measured in a complex intertwined shielding-conductor system with non-metallic and metallic materials and subsequent mechanical fatigue?

To this end, a method will be developed to provide these characterizations in coaxial cable systems.
CHAPTER 4
EXPERIMENTAL METHODOLOGY

This research involved several procedures. Each conductor-shield coaxial system was formed into three identical cables, each of which was characterized using scattering parameters. Low frequency and high frequency shielding tests were conducted using a bare conductor and receiving antenna within a mode-stirred reverberation chamber. Each cable was fatigued and the characterization and shielding tests were repeated.

4.1 Materials Selection

Several materials were selected for use within coaxial cables because of prior review of research and promising properties observed. Materials used within coaxial cables prototypes as center conductors and shields generally are: electrically conductive, flexible, strong, ductile, resist fatigue, conformal, and affordable. Certain applications prioritize some of these qualities over others for optimal materials selection.

For the case of avionics, it is highly advantageous to use low density materials for cabling to conserve weight. As demonstrated in Sections 2.6.1 and 2.6.2, carbon nanotube materials were of interest since they are conductive, resist fatigue, are flexible, and have low density.
Nanocomp Inc’s carbon nanotube tape and yarn were chosen as a shield and center conductor respectively since at the time of prototype production they were one of only a handful of commercial producers of amorphous, pure carbon nanotube tapes and sheets. Nanocomp’s carbon nanotube materials are composed of multi and double walled carbon nanotubes. Their materials are produced in a proprietary method; however, they use a floating catalyst chemical vapor deposition process. Their products have nanotubes on the order of a millimeter in length that can be manufactured on a large scale; sheets can be purchased up to 54 inches wide by 8 feet long [93]. In addition many studies have investigated Nanocomp products for use in coaxial cable prototypes before [26, 80-82, 94] demonstrating results that warrant wider, comprehensive, and more in depth investigation.

Applied Science Inc.’s Pyrograf III was also selected to be used as a shield material. Applied Science claims their Pyrograf III nanofibers to provide the highest conductivity to lowest loading of any commercially available conductive filler. What this translates to is potentially high cost savings compared to the Nanocomp nanotube products. Applied Science also promises the same improvement in mechanical strength as other carbon nanotube fillers, “it improves modulus, strength, fracture toughness, and fatigue resistance.” [95].

These two novel materials were compared to traditional cabling materials. Silver coated copper clad steel is one of the most commonly used. Wires and cabling are frequently comprised of silver coated copper clad steel since it takes advantage of the super high conductivity of silver and copper at the surface and combines it with the strength and durability of steel. Silver is used on the outer most layer since it is the most conductive (most expensive), and this is where the majority of the current will flow especially at higher
frequencies due to the skin affect. Copper is beneath the silver, as although it is not as expensive, it still very conductive. This is more pertinent as lower frequencies where the skin depth is larger and more current will flow within the copper. Silver and copper both also have the benefit of resisting corrosion. Steel provides high mechanical resistance and is much less costly. Most all the current remains in the silver or copper especially at the frequencies of operation, so the relatively low (compared to silver/copper) conductivity of steel is irrelevant. These shields/conductors are also incredibly well characterized and regulated. ASTM standard B501-10 details the exact specifications (in weight percentages) required for silver coated copper clad steel for electronic applications [96].

4.2 Cable Construction

In terms of architecture of the prototypes, the goal of the novel cables was to closely approach actual manufacturing capabilities. Jarosz et al. noticed when assembling cabling prototypes themselves, that attenuation about doubled for even the same type of cable compared to an as manufactured cable [80]. In other evaluations in the lab differences of ten to twenty decibels are seen for cables with inconsistent shield or heat-shrink application. Using professional manufacturing methods not only made these cables more comparable to commercially available cables but allows for a more accurate assessment for use within large scale application. What good are long length cylindrical carbon nanotube sheet wraps if materials can’t be fabricated in large/long enough sample sizes or manufacturing such a construction is not feasible? In addition, a cable braider, a multi-million-dollar piece of machinery, was not available in house for use. All prototypes were produced in conjunction with Minnesota Wire.
A helical wrap was selected for novel material shields. Manufacturing currently occasionally uses such a design and is often used for materials such as aluminum (which is sometimes used for lower frequency shielding). A five eighths inch wide commercially available, carbon nanotube tape was selected to be used within many of the prototypes. Each wrap is approximately 50 microns thick. In addition, the Applied Science Inc. product was formulated into 250 microns thick, eighths inch wide tape as well for more direct comparison to the Nanocomp product.

A silver-plated copper clad steel thirty-eight American wire gauge at six picks per inch was selected as the commercial point of comparison. One major goal of this research is to investigate how competitive a commercially manufactured cable consisting of these novel materials is and the best way to do that is by comparing it to a widely used standard. In this case that is by comparing novel shields to a silver coated copper clad steel braid. Braids are ideal for cabling because they allow for flexibility and strength. It also has higher surface area to interact with any field. A tight braid does not leave much exposure to the center conductor; this protects the internal signal from incoming fields and from leaking out. Ensuring maximal coverage and characteristic impedance is what determines which braider will be used and the gauge and pick density.

Table 4.1 shows the material construction of each prototype variety. A sample size of three articles per each construction was selected due to cost constraints.
Table 4.1: Prototype Constructions.

<table>
<thead>
<tr>
<th>Core</th>
<th>Shielding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undoped Carbon Nanotube yarn</td>
<td>2 Braids of silver coated copper.</td>
</tr>
<tr>
<td>Undoped Carbon Nanotube yarn</td>
<td>2 wraps of 2 layers undoped Carbon Nanotube tape.</td>
</tr>
<tr>
<td>Silver plated copper clad steel</td>
<td>1 wrap of 2 layers undoped Carbon Nanotube tape.</td>
</tr>
<tr>
<td>Silver plated copper clad steel</td>
<td>2 Braids of silver coated copper.</td>
</tr>
<tr>
<td>Silver plated copper clad steel</td>
<td>2 wraps of 2 layers undoped Carbon Nanotube tape.</td>
</tr>
<tr>
<td>Silver plated copper clad steel</td>
<td>1 Braid silver coated copper.</td>
</tr>
<tr>
<td>Undoped Carbon Nanotube yarn</td>
<td>1 wrap of 2 layers undoped Carbon Nanotube Tape.</td>
</tr>
<tr>
<td>Undoped Carbon Nanotube yarn</td>
<td>1 Braid silver coated copper.</td>
</tr>
<tr>
<td>Silver plated copper clad steel</td>
<td>1 wrap ASI Carbon Nanofiber tape.</td>
</tr>
<tr>
<td>Silver plated copper clad steel</td>
<td>2 wraps ASI Carbon Nanofiber tape.</td>
</tr>
</tbody>
</table>

4.3 Cable Fabrication

An RG-316/U cable construction was selected for the commercial cable point of comparison and as the construction standard for prototype cables. RG stands for Radio Guide and the U stands for universal. Many types of coaxial cables were designated by a former military handbook and are now categorized for commercial industry. The type RG-316 (or RG-316/U) is a single shielded coaxial designed to run with a fifty Ohm load at relatively low attenuation, approximately 7.5 dB of attenuation over 100 feet of cabling at 50 MHz. It can operate across a wide band of frequencies. Metal systems are terminated and crimped to a subminiature version A (SMA) connector, which is most useful in communication connections, such as to telephone antennas or radios. Carbon based
systems are connected to the SMA using silver Loctite to form an electrical bond and proper structural bond. The SMA is beneficial as it operates from about direct current up to about 18 GHz.

4.4 Cable Characterization Technique

Coaxial cables were characterized using a two-port test method on an Agilent Technologies E8362C Network Analyzer. The scattering parameters (S-parameters), S_{12}, S_{21}, S_{11}, and S_{22} were measured from 10 MHz to 20 GHz. Each measurement was averaged over eight sweeps per cable. A sixteen-pound calibrated torque wrench was used to ensure consistency in the mechanical contact of the subminiature version A (SMA) connectors to the analyzer test cables. A 3.5mm Agilent calibrated E-Cal kit was used to reduce the influence of noise as well as any contribution from the test leads and connectors.

Previous methods to calibrate such systems used to involve using a short, open, load, and thru connected to the test leads. Using these four known standards (short, open, load, and thru) a series of twelve measurements were made by a user to resolve possible errors (such as signal leakage, crosstalk, signal reflection, etc.). The E-Cal kit and program module reduces the user error and time involved by electronically switching several different impedance states to the test leads and averaging ten signal sweeps for the system. A calibration was performed prior to each continuous round of characterization on the test samples by connecting the system test leads to the E-Cal kit and using the calibration module.
From the scattering parameters, other pertinent properties can be calculated for each cable. These intrinsic features include the cable power insertion loss, as seen in the equation below:

\[ \text{IL(dB)} = -20 \log |S_{21}| \]

The insertion loss is a measure of the inherent resistance of a cable or the energy lost as a signal is sent down the transmission line. Aspects such as cable connectors, conductor diameter, and cable length affect the insertion loss. The forward reflection coefficient, \( \Gamma \), is also a function of the scattering parameters.

\[ \Gamma \text{(dB)} = 20 \log |S_{11}| \]

The reflection coefficient is highly related to the return loss, RL, which is the magnitude of the reflection coefficient expressed in decibels, or:

\[ \text{RL} = -20 \log |\Gamma| \]

The return loss gauges the reflection of signal from inserting a device into the system and cable. It is a ratio of the reflected power compared to the input power. A higher return loss usually indicates that the connected device is receiving a greater majority or the power, which in most instances is desirable.

The complex linear gain is simply the S21 parameter, or as expressed in terms of voltages, would be:

\[ G \text{ (dB)} = 20 \log |S_{21}| \]
The voltage standing wave ratio, VSWR, is also related to the magnitude of the reflection coefficient as well by,

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|}.$$

In many cases a connected device, such as an antenna, can reflect back waves towards the source due to impedance mismatches. This can further hinder power being transmitted to the device by potentially distorting the oncoming wave. The voltage standing wave ratio quantifies this distortion by measuring the ratio of the voltage peaks to the valleys (i.e. the maximum and minimum voltage). Ideally the voltage standing wave ratio would be equal to one. The VSWR indicates how well matched the device under test is to the system. In this research cables should be impedance matched to 50 Ohms.

These cable parameters are integral for circuit design and electrical application. Knowing parameters allows for correct system design and properly matched components. As an example, instruments running on low return loss circuitry probably will not receive adequate power and thus will not function properly. In addition, cable characteristics lead to proper design criteria for the system, such as the correct length of cabling or the inclusion of an amplifier.

These parameters are also a good indication of the conducting capability each cable has, and whether there is much attenuation over the length of the cable (i.e. how much power is lost from beginning to end of the cable). Conducting capability becomes significant when considering how well a cable is shielding. In order to know how much an
external field is disturbing a signal transmission, one needs to know how effectively the signal is being transferred in the first place.

4.5 Primary Electromagnetic Low Frequency Shielding Procedure

After cable characterization, samples were examined using the facilities at National Institute for Aviation Research (N.I.A.R.) at Wichita State University in Wichita, Kansas and N.I.A.R.’s Electromagnetic Effects Laboratory.

Two different sets of initial electromagnetic shielding tests were conducted. A calibrated FCC brand current injection probe was used at a frequency range of ten kilohertz to one gigahertz inside of a reverberation chamber. The injection probe was used to measure the shield’s magnetic field response. The test diagram can be seen in Figure 4.1 and the test set up can be seen in Figure 4.2. The cable under test was grounded to the aluminum test fixture by connecting the cable to a calibrated 50 Ohm load and the other end of the cable connected to the measurement side of setup which fed into the control room to a spectrum analyzer via a raised RG-402 shielded copper hardline radio frequency cable. The forward power from the amplifier was set to 20 dBm +0.3/-0.0dBm for all test frequencies.
Figure 4.1: Shielding Effectiveness Low Frequency Response Test Setup Diagram.

Figure 4.2: Shielding Effectiveness Low Frequency Response Test.
A signal generator and amplifier created the source signal which was fed into the reverberation chamber to the bulk injection probe clamped over the cable under test on a centered spacer. At each frequency, the spectrum analyzer measured the peak power on each cable as a comparison to a baseline unshielded cable giving a shielding effectiveness of the cable under test as seen in the equation below.

\[ \text{Cable Under Test Shielding Effectiveness (dB)} = \text{Unshielded Cable Power (dBm)} - \text{Cable Under Test Power (dBm)}. \]

### 4.6 Primary Electromagnetic High Frequency Shielding Procedure

An eleven feet high by seventeen feet wide by twenty-five feet long reverberation chamber with a rotating Z-fold paddle was used to create a statistically uniform, isotropic, randomly polarized electromagnetic field. This field generates a robust real-world test scenario for evaluating shielding effectiveness at high frequencies.

As with the low frequency evaluation, the test cable was configured in a similar manner; the labeled side of the cable was connected to the measurement end of the test fixture via shielded RG-402 copper hardline. The cable was grounded to the fixture and terminated by a calibrated Bird 50 Ohm load. This was done for frequencies up to 2 GHz after which a different 50 Ohm termination, from a calibration kit, was used that had a lower voltage standing wave ratio at higher frequencies.

The source signal was created by a signal generator and amplifier which was fed into the room to a transmission antenna (either a log period antenna below 1GHz or a horn antenna above 1 GHz) as seen in Figure 4.3. For every frequency setting of the spectrum analyzer, one full rotation of the paddle wheel occurred and the peak power of the test cable
was measured. Measurements were compared to a baseline cable as well as to a receiver antenna in the room which may help to eliminate the appearance of standing waves in shielding data. High frequency tests were run from 100 MHz to 18GHz.

Figure 4.3: Shielding Effectiveness High Frequency Response Test Setup Diagram.
4.7 Fatigue Procedure

After the initial electromagnetic shielding measurements, the cables were mechanically fatigued using the Mechanical Test Labs at the National Institute for Aviation Research of Wichita State University. A low cycle fatigue process was chosen for several reasons. Due to time constraints and machine capability a low cycle method was more practical. With the test stand upper frequency limit of 2 Hz and many, many cables to fatigue, as well as the necessity of constant supervision, cycling cables on the order of days was not feasible. Secondly one of the main applications for ultra-low-density cabling would be avionics. In this field variations in conditions are much more extreme. Temperature, pressure and environment change dramatically through the lifetime of the cable. A low
cycle fatigue is practical for probing articles that must withstand large variations of conditions [97].

Two four-point resistance tests were performed in-situ fatigue tests utilizing two Keithley 2400 source meters as seen in Figure 4.5. This was done to determine if and when and where failure occurred in each sample. A four-point test was performed on the shield as well as on the conductor for each cable. The resistance was monitored at a rate of roughly five data points per second. This information was necessary to indicate when discontinuities occurred from fatigue. Also, if a portion of the sample cable broke, the data showed whether it was in the shielding of the cable or the conductor which is vital to discern for later electromagnetic tests.
Monotonic load based tensile tests were performed on three RG-316 commercial off the shelf samples. An average ultimate tensile strength was then determined. Fatigue tests were cycled from 50% to 10% of the ultimate tensile strength at 2 Hz to prevent slack from forming. The frequency of 2 Hz was chosen since the duration of the tests had to be minimized to complete testing on the order of days, rather than weeks, and it was unknown how many cycles each sample could endure. This was also the limitation of the instrument.
Ten-inch test segments were used for each sample cable measured from the end of each grip. Cables were secured via bollard grips to the load frame using a 25-inch pounds torque wrench as seen in Figure 4.6.

![Load Frame Setup for Monotonic and Cyclic Fatigue Tests](image)

**Figure 4.6:** Load Frame Setup for Monotonic and Cyclic Fatigue Tests

Because of the exceedingly high economical costs of fabricating cables, no spare novel cables were created for this study. Nanocomp Inc., the manufacturer of the carbon nanotubes and tapes within the novel cables shields and center conductors, claims their products to be quite strong. They cite a “two orders of magnitude” increase in strength compared to copper cable and an ultimate tensile strength of 2.06 GPa for their yarns (which was used as a centerline conductors) [90]; Jarosz et al., as detailed previously, also
cited a tensile strength on the order of gigapascals. Because of this, commercial off the shelf RG-316 type coaxial cable was used as the standard by which to perform fatigue tests to. This was also done since novel cables would be expected to be utilized and treated the same as current cabling. Monotonic tests were performed using three RG-316 cable samples. From this an average tensile strength was calculated to use for the cyclic loads of the fatigue tests.

Fatigue tests were conducted at 2 Hz at an R value of 0.2, to $10^2$ cycles or until failure on a Sabre load frame. Tests would have been continued to further cycles, however novel cables failed long before expected. To maintain consistency, all cables were run to $10^2$ cycles. The peak load was 32.8 lbf and the minimum load was 6.56 lbf.

4.8 Repetition of Characterization and Shielding Procedures

To determine deterioration of transmission due to the physical damage of fatigue, the cable characterization of each cable was repeated. This is important as it assessed how well a cable conducts after being fatigued. This will be used to determine if each system can still efficiently carry signals even after it has been worn out. This is necessary to ensure that any discrepancies in conductivity are not falsely attributed to an increase in shielding.

Electromagnetic shielding tests were then repeated (as was done before) to determine the effect fatigue has on the integrity of the shielding. It is desirable to have a cable that can be heavily used, experience strain, and still shield well. Preforming post fatigue electromagnetic shielding tests best determines that for both novel and commercial cables.
4.9 Novel Outcomes

This novel developed technique will offer more accurate measurement methods for non-metals in coaxial geometries both as a shield and as a conductor. Going forward it can be applied to novel shield or conductor materials currently in development. It will also gauge the effect mechanical fatigue has on the shielding effectiveness and the signal characterization. It will reduce the effect of impedance mismatches that occur as a function of frequency on shielding data. This will also lead to an ability to select appropriate shields for specific frequency applications without the concern of constructive conductor interference being construed as well performing shields. This will lead to improved testing of low density, cost saving materials and further safe circuitry designs.
5.1 Nanomaterial Composition

Both Nanocomp and Applied Science Inc. (ASI) raw carbon nanomaterials were characterized to determine approximate chemical composition and to investigate mechanical and electrical properties.

X-ray photoelectron spectroscopy (XPS) was conducted on both carbon nanomaterials using a monochromatic aluminum K-α source. The following compositions were determined using background subtraction and peak fitting.

Table 5.1: X-ray Photoelectron Spectroscopy Results of Nanocomp and Applied Science Inc. Nanotube and Nanofiber Materials.

<table>
<thead>
<tr>
<th>XPS Line</th>
<th>Atom %</th>
<th>XPS Line</th>
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<tbody>
<tr>
<td>C 1s</td>
<td>84.1</td>
<td>C 1s</td>
<td>90.8</td>
</tr>
<tr>
<td>O 1s</td>
<td>13.4</td>
<td>O 1s</td>
<td>7.7</td>
</tr>
<tr>
<td>N 1s</td>
<td>1.4</td>
<td>F 1s</td>
<td>0.9</td>
</tr>
<tr>
<td>S 2p</td>
<td>1.2</td>
<td>Fe 2p3</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Considering this is a type of surface characterization of carbon nanomaterials, a certain level of contamination is to be expected, especially of atmospheric (i.e. air) elements. In this case XPS revealed a primary composition of both samples to be carbon, which is to be expected for carbon nanofibers and nanotubes. The primary bonding is of C-C which shows as the large C 1s peak at around 284 eV. Oxygen is also present which is likely from exposure to air. Fluorine has been observed as a surface contaminant in Nanocomp samples before and has been attributed to the likely outgassing of nearby materials such as Teflon [98]. Another possibility is exposure to tap water, which may have been treated with fluorine, during processing. Interestingly, the Nanocomp nanomaterial has roughly half a percentage or iron which is likely remanence of the iron floating catalyst used in manufacturing [98]. Applied Sciences uses sulfur as an addition to enhance filament nucleation during carbon nanofiber production [99] which is why there is sulfur seen at the material surface.

5.2 Pre-Fatigue Signal Characterization

Initial cable characterizations are shown for each conductor-shield system. Results are compared and contrasted to give indication of the performance of each cable constituent. Signal carrying capability is assessed over the sampled frequency range. In addition, signal analysis will be used later to determine the effect of shielding effectiveness for the coaxial system.

Representative characterizations can be seen in the following figures.
The characterization for a copper core conductor and commercial off the shelf copper shield shows more minimal insertion loss reaching a total loss of just over 6 dB at 20 GHz. In addition, the return loss is quite high, around 25-30 dB. This means a vast majority of the power would be correctly delivered to any matched device connected. This also goes to show that even though the system is designed as a 50 Ohm characteristic impedance cable, the real portion of the impedance does not remain at 50 Ohms. This is more likely at higher frequencies due to radiative losses through the shield apertures.

Figure 5.1: Copper Core with Copper Braided Shield Characterization.
The characterization of the copper core conductor shows relatively low insertion loss again more typical of the copper conductor due to its high conductivity. The return loss shown in the lower left graph shows less power being transferred to the end of the line at higher frequency ranges. This may be due to radiative losses from the conductor through an inefficient shield. The voltage standing wave ratio has less overall variability and noise than the copper core with copper braided shield cable. In addition, it does not reach as high maximums.

**Figure 5.2:** Copper Core with Double Carbon Nanotube Wrap Shield Characterization.
Figure 5.3: Carbon Nanotube Core with Copper Shield Characterization.
Figure 5.4: Carbon Nanotube Core with Carbon Nanotube Double Wrap Shield Characterization.
Carbon nanotube yarn based center conductor samples exhibit high insertion loss (as seen in Figure 5.5) and high impedance signal carrying capability. This is largely due to the fact that conductivity of the macro-scale carbon nanomaterials is not near as high as that of silver or copper. In addition, electrical contact between SMA connectors and non-metals is difficult to achieve which could also effects system impedance and insertion loss.

The shielding, which is discussed in further detail in the following section, also can dictate the signal carrying capability. For example, carbon nanotube sheet shields do not shield well particularly at low frequencies, as the sample shields employ reflection and the skin effect (which increases with increasing frequency). This means signal can be lost.
through radiation in those samples particularly at lower frequency ranges. At higher frequencies for carbon nanomaterial shields, the skin effect drives improved reflectance and shielding, thereby protecting transmitted signal more as frequencies increase. For copper braid shielded samples, shielding plays a large role at higher frequencies where the apertures within the braids are more significant to the size of the smaller radiative wavelength. This means more signal radiates out at higher frequency ranges for these samples [91].

For the purposes of developing a novel measurement for shielding effectiveness, one aspect of the cable characterizations is important to examine further. The voltage standing wave ratio, or VSWR, as mentioned, is the indicator of how well matched a cable is to a system (in this case a 50 Ohm system). The voltage standing wave ratio in these characterizations closely follows the real impedance. A lot of times a cable may not be matched to the load, and not all the power gets delivered. A lot of the power may get reflected back or attenuated and does not make it to the load. In this case, the VSWR is greater than one. Ideally the VSWR is one and the cable is matched to the system and the maximum and minimum/peaks and troughs have the same magnitude.
Figure 5.6: Voltage Standing Wave Ratio for Silver Coated Copper Clad Steel Core with Silver Coated Copper Clad Braid as a Function of Frequency.

Figure 5.6 shows the voltage standing wave ratio for a traditional cable compromised of silver coated copper clad steel core with a silver coated copper clad braid shield on a logarithmic x-axis. The overlaid line indicates the interpolated points used for the frequencies tested within the reverberation chamber. These VSWR calculations are the same as the characterization calculation previously except reexamined and interpolated for a comparison for shielding measurements.
Each baseline, unshielded core, was examined as it shows how well or poorly the center conductor alone is matched to the load. This highlights the mismatch of the baseline without the shield in place and gives indication of the frequencies shielding effectiveness measurements could be falsely inflated or inaccurately reported for the system. Comparing to the figure above, Figure 5.7, this demonstrates the interaction between the center conductor and the shield, just how important the shield is for transmitting signals properly.
Figure 5.8: Voltage Standing Wave Ratio for Carbon Nanotube Yarn Core with Double Wrap Carbon Nanotube Shield

Figure 5.8 shows the VSWR for the carbon nanotube yarn with the double wrap of carbon nanotube tape. The VSWR is always a little higher than engineers would typically like. A VSWR of about 1.5 means that about 96% of the power is making it to the load. At higher frequencies, much like with the copper braid, the shield may be responsible for loss and high VSWR.
Figure 5.9: Voltage Standing Wave Ratio for Unshielded Carbon Nanotube Yarn

The VSWR of the carbon nanotube yarn center conductor is quite high especially in the lower frequency range. A lot of the signal would not make it to the attached device or load without the presence of the shield as seen in Figure 5.9. It appears the shield retained a lot of the power for the carbon nanotube yarn. As discussed in section 2.6.1.1 and section 5.4.1.2.1., the conductivity of carbon nanotubes is frequency dependent and below the 100 MHz range the conductivity is rather low in comparison. As frequency climbs, conductivity improves and more power is transmitted to the load.

5.3 Adjustments in Shield Effectiveness Data Using Cable Characterization

To accurately access systems of their ability to prevent electromagnetic interference, the impedance mismatch to fifty ohms is taken into account of both the cable under test and the unshielded cables without the presence of an external field.
Ideally, a cable that is perfectly matched to the system it is operating with will have a voltage standing wave ratio of one to one (or just one). This means that the amplitude of the maximum of the signal wave is equal in magnitude to the minimum of the signal. Anytime there are internal reflections, loss, or an excess of power this wave gets distorted and the wave maximum and minimum are no longer the same magnitude due to constructive, destructive, or general interference. This is often the case when a conductor does not transmit signal properly across the specified frequency.

Looking at signal characterizations, it is clear that some of the cable prototypes do not maintain a perfect peak to trough magnitude equality. This is observed within the voltage standing wave ratio, or VSWR, measurements most clearly. Furthermore, the real portion of the impedance measurements verifies this. A perfectly matched coaxial system would have an impedance of fifty ohms across the operating frequencies. When a relatively well-matched cable is removed of its shield, the way it transmits signals is greatly altered. It is no longer impedance matched to the system and its voltage standing wave ratio is no longer one. This matters particularly when assessing interference. When a shielded cable is compared to an unshielded cable, any differences between the two cable signals within an electromagnetic field is entirely attributed to interference and gets lumped into the shielding effectiveness measurement of the shielding material.

In this research each signal power measurement, of both the shielded and the bare cable, is normalized using the voltage standing wave ratio without the presence on an external field. This thereby accounts for impedance mismatches, any constructive or destructive interference inherent to the cable signal, or discontinuities present in the cable. Shielding effectiveness is thereby calculated using the following equation:
\[
SE = \frac{P_{\text{baseline}}}{VSWR_{\text{baseline}}} - \frac{P_{\text{cable under test}}}{VSWR_{\text{cable under test}}} - \Delta FW P
\]

In addition, this method accounts for signal that is lost when there is no shield present that often gets lumped into the effectiveness of the shield. This normalization takes into effect both the case when a shield is present and therefore the voltage standing wave ratio is closer to one and the case when there is no shield, when the voltage standing wave ratio gets quite large, and normalizes them out. Only the change in signal coupled to the center conductor due to the ingress of the external field with the presence of a shield is now measured. The extremely small difference in the forward power sent on the cable under test and the baseline cable is also taken into account so as not to get attributed to any coupling differences.

5.4 Pre-Fatigue Cable Shielding

Initial shielding (pre-fatigue) results can be seen in Figure 5.10 and Figure 5.11. Results are shown for a bare cable comparison for individual cables. While this initial, unadjusted, data does not consider standing waves or impedance mismatches, it does take into account that the core conductor does not have perfect conductivity or behave like a perfect monopole antenna.

This data is compared back to a bare RG-316 silver plated copper clad steel core conductor. The shield of the cable has been completely removed. A bare carbon nanotube yarn cable core was also inspected and showed near identical coupling to that of the silver plated copper clad steel core. For initial results, the metal core is used as the baseline to compute the shielding effectiveness for each cable, regardless of the center conductor. With
adjustments, any differences in bare cable coupling are accounted for. In antenna compared data, shielding effectiveness appears higher, while in actuality the core conductor is simply not conducting the signal perfectly. The reference antenna is also only being utilized in the higher frequency, radiated, tests.

Figure 5.10: Low Frequency Shielding Effectiveness Results.
**Figure 5.11:** Raw Analysis: High Frequency Shielding Effectiveness Results.

Figure 5.10 and Figure 5.11 do indicate significant differences between the shielding effectiveness of copper based shields and carbon-based shields. Carbon based shields have poor shielding in the lower frequency ranges shown in Figure 5.10. For carbon nanotube and nanofiber type shields, there is almost no shielding as the frequency approaches closer to direct current. The commercial off the shelf type shields, which are the copper braid style, have much more effective shielding until the higher frequency range of 2.4 GHz. The carbon nanotube based shields, on the other hand, show markedly
improved effectiveness around 4.5 GHz. The carbon nanofiber shields of ASI also show similar effectiveness improvements in this range, although not quite to the same extent. In addition, in this region the traditional copper braid shield starts to show larger declines in shielding effectiveness. Further post processing will provide greater insight into each material mechanism and better analysis methods.

Figure 5.12: Corrected Pre-Fatigue High Frequency Shielding Effectiveness Results.
Figure 5.12 shows the corrected shielding effectiveness results for all the samples according to the method established in section 5.3 that accounts for differences in centerline conductor materials and impedance mismatches of both the cable under test and the baseline unshielded cable. Each shielding type is discussed in further detail.

5.4.1 Carbon Nanomaterial Mechanisms

5.4.1.1 Carbon Nanomaterial Shielding Measurements

Shielding effectiveness adjusted measurements of the cables with a carbon nanomaterial shield at the higher frequency range begins at about zero decibels or slightly below as seen in the figure below. Because of issues within connectorization, initial shielding can be below zero. This is because with poor connection of the shield, a grounded faraday cage is no longer formed with the shield around the center conductor. The shield can begin to act like an antenna allowing further signal, and in some cases even concentrations of interference, to enter and affect the center conductor. This was emphasized in some rare instances where the connectors began separating from the cable. Additionally, subsequent fatigue did not help this as can be seen in later discussion and figures.
Carbon nanomaterials at these lower frequency ranges show no impressive shielding effectiveness, barely reaching ten decibels. There are multiple reasons for this. Bulk/macro scale carbon nanomaterials have several limiting factors.

**Figure 5.13:** Carbon Nanomaterial Shielded Cabling Shielding Effectiveness.

A focused beam analysis of a single planar sheet of Nanocomp paper can be seen in Figure 5.14 (note the left axis corresponds to Reflection percentage and the right axis corresponds to the Transmission and Absorption percentage; this data is gated to reduce errors from most machine and fixture noise). This data represents the calculated amount of
power transmitted, reflected, and absorbed as a percentage of total observed power. The absorbed power also incorporates the possibility of destructive reflection off the sample. This could occur at a very narrow range of frequencies, especially if multiple reflections were taking place, indicative of the thickness of the material. Very small fluctuations are more evident given the scales used; however, this material blocks the clear majority of power in the sampled range. In addition, with reflection values so consistently high and minimal total loss of power (net power measures just about 100%, some minimal additions may be due to radiation from nearby devices, mobile phones, radiation scattered off the measurement plane, etc.). This means that very little signal is being let through.

**Figure 5.14**: Nanocomp Carbon Nanotube Sheet Scattering from Focused Beam Measurement (Left Axis: Reflection, Right Axis: Transmission and Absorption)
The primary mechanism by which this material is shielding is via reflection (or multiple reflections) because nearly all the power/radiation is being reflected back. In order to reflect radiation a material must possess mobile charge carriers in order that they may interact with incoming waves. This is more preferential at the surface of incident radiation. Multiple reflections require similar principals; however, it relies on high surface areas/interface areas where such reflections can occur. Multiple reflection contributions are also ignored when the thickness of the material is one skin depth or greater [103].

The mechanism of reflection is most dependent on material conductivity and frequency and is enhanced by connectivity [6, 103]. Conductivity for such bulk amorphous carbon nanotube materials is currently limited by the complexity and number of nanotube junctions as discussed in section 2.5.

It is also important to note that the sample used in this calculation is a planar continuous sheet (without any center conductor). The cable shield is not seamless. One inhibition to connectivity/conductivity in shields is that the material is not continuous. There are up to two wraps (each of which is 25 microns thick with a 50% overlap, totaling 100 microns) and the width of the tape is 5/8th inch (15.875 millimeters). There are many additional barriers by which electrons must travel through.

The cable shields, however, are able to reflect relatively efficiently and this increases with frequency. As frequencies begin to increase from 100 megahertz, the skin effect becomes more prominent. The electromotive force forcing current to the skin becomes higher at higher alternating current or frequency. The skin depth lowers as frequency increases per the following equation (where $f$ is frequency) [6, 10, 11]:

$$\delta = \frac{1}{\sqrt{2\pi f \mu \sigma}}$$
\[ \delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \]

There is higher current density toward to the surface of the incoming radiation. This means there are more mobile charge carriers available to interact and deflect the external field more efficiently. With each skin depth, the power at that depth is decreased by a factor of \(1/e\) to what it is at the surface \([6, 10, 11]\).

At lower frequencies, the carbon nanotube shield does not have enough thickness to reduce the incoming radiation. Jarosz et al. measured the skin depth of Nanocomp carbon nanotube sheets to be one hundred microns in thickness at one gigahertz. This deduction was made by noticing the thickness which no additional attenuation took place, as no significant changes in protection occur after four skin depths \([80]\) (over 99% of the current is contained to 4.6 skin depths towards the surface \([105]\)). This technique of calculating could be somewhat inaccurate considering they also cited issues of around a two-fold difference in attenuation due to deconstructing and reconstructing cables. This does, however, give a very rough estimate of skin depth for the measured carbon nanotube tape materials.

The carbon nanotube tape shield of two wraps in the measured cables has an approximate total thickness of about 93.6 to around 100 microns. According to Jarosz et al., this would imply these cables have roughly one skin depth at a frequency of one gigahertz. It is worth noting the format of this shield is a helical tape, whereas Jarosz’s study is a cylindrical wrap of a single sheet. With this format, there is an introduction of resistance from the existence of spacing between wrap to wrap. An approximate skin depth
of 31.6 microns can be calculated utilizing the adjusted shielding effectiveness of copper clad steel center with double wrap of carbon nanotube tape, of 12.84 dB at 1 GHz. A shielding effectiveness of 12.84 dB is equivalent to a shielding efficiency of 94.88% or only 5.199% of the incoming power coupling. This means the initial field was reduced by \( 1/e \), 2.96 times. At a total thickness of 93.6 microns, that would mean each skin depth is 31.6 microns.

Skin depth, or the thickness necessary to potentially deflect the incoming field, reduces as a function of frequency and conductivity. This explains the upwards trend in shielding effectiveness seen in carbon nanomaterial shields. The total thickness of the shield remains the same. However, as frequency increases more current/mobile charge carriers are brought efficiently towards the interacting surface. The skin depth decreases and current density at the surface increases. Each factor \( (1/e) \) of reduction of radiation requires less skin depth to attenuate the field, all up until about 4.6 skin depths, where over 99% of the power is mitigated [105].

There is, however, a contradicting factor that does come into play. As frequency gets higher and higher, wavelengths get lower and lower and the ability of the external field to penetrate perforations, small holes, seams, and any opening increases. Although the wrap shield has higher coverage than a braid for example, it is still slit, wrapped, and non-continuous. This is likely what is beginning to occur at the upper frequencies towards 10 GHz. This is sometimes referred to as the shield cutoff frequency. Even constructions with several types of shields, or maximum coverage, have frequencies at which their shielding effectiveness starts to decline. Usually multiple shields and higher coverage increases the frequency range of the point of decline [106].
5.4.1.2.1 High Frequency Conductivity and the Skin Effect in Carbon Nanotube Materials

The skin effect and the conductivity are interrelated. The skin effect, and in this case, how efficiently radiation is shielded by a material, is largely dependent on the impinging field frequency and the conductivity of the material. The conductivity of carbon nanotube materials also varies with frequency. When alternating current travels through a medium it has a magnitude but it also has a phase, and the response of the material is not always instantaneous. This happens because electrons require some time to accelerate in response to the change in alternating field. This time scale can become particularly important for non-crystalline or non-homogenous materials. Kinetics, such as electron collisions between positive ions or other electrons, and barriers or discontinuities come into effect. Also at high enough frequencies, band structure can play a role in conductivity, though the frequencies investigated in this study are unlikely in that range [32].

In addition, when current passes through a medium, the eddy currents can confine the current density to the very edge of the material and inhibits flow towards the center. This reduces the effective area of conduction and can increase overall resistivity at high enough frequencies [6, 10, 11]. In the case of shielding, this is, in part, what allows for the formation of a faraday cage with more efficient surface interaction and reflection due to the large presence of mobile charge carriers at the materials surface, i.e. the skin effect [6, 8].

Conductivity of carbon nanotube materials, as summarized in section 2.6, varies across a wide band of frequencies. Several studies measure and fit the conductivity of
single and multi-walled carbon nanotube materials to an extended pair approximation with excellent fit, particularly below about 10 GHz. The extended pair approximation follows:

$$\sigma = \sigma_0 [1 + k \left( \frac{\omega}{\omega_0} \right)^s]$$

Where $\sigma_0$ is the direct current conductance; $s$ which is less than or equal to 1.0, describes the relative disorder of the system ($s$ approaches one as disorder increases); $\omega_0$ is the onset frequency; $\omega$ is the frequency, and $k$ is a fitted parameter [28,32,107]. The onset frequency of the alternating current conductance increases as the direct current conductance increases.

The conductivities for several different single walled carbon nanotube film samples with varying densities were measured by Xu et al. and plotted using the extended pair approximation, as seen in Figure 5.15 [32].
Figure 5.15: Real Parts of the A.C. Conductance for Samples with Different Densities at Room Temperature. The Black Crosses Mark the Fitted Onset Frequency. (b) The Onset Frequencies vs. D.C. Conductance of Single Walled Carbon Nanotube Networks. The Solid Line has Slope of One (Reproduced with Permission of The American Physical Society) [32].

This alternating current behavior of carbon nanotube network films, at which conductivity increases at certain onset frequencies, is explained by Kilbride et al. and Xu et al. by the correlation length. The correlation length is defined as the approximate distance between junctions of the multiply connected nanotube network. As previously discussed, conductivity of carbon nanotube materials is largely dependent on the resistance and presence of network junctions. When a sample is in the presence of an alternating current, the frequency at which the current is oscillating correlates to a length scale being probed, as charge carriers will only travel so far over the course of each current oscillation.
At lower frequencies, or longer temporal periods, carriers travel longer distances/lengths. At higher frequencies, or shorter temporal periods, carriers travel shorter lengths per current cycle [32, 37]. This means at low frequencies the length being probed spans many, many nanotube junctions and can play a higher role in the conductivity measurement (as the resistances between tubes are higher than the resistance of an individual tube). The conductivities at these frequencies is therefore smaller and closer to that of the direct current range [32, 37].

As frequencies slowly increase of an imposed alternating current, the corresponding distances or lengths being probed are smaller so the high resistance nanotube junctions have less influence on the measured conductivity. Stimulating current at higher frequencies, correlating to smaller length scales, allows for the electrical properties of the nanotubes themselves to dominate conductivity measurements. The onset frequency, or transition frequency, is the expected frequency at which the average distance scanned is of the order of the correlation length. Xu at al. explains that as the density of the single walled nanotube networks increases, there are more junctions and the correlation length, being the average distance between connections is smaller, so the onset frequency thereby increases [32, 37].

Using the focused beam measurement scattering parameters, it is possible to calculate the permittivity of the Nanocomp carbon nanotube material for the planar sheet. From this, the conductivity can also be calculated. Using the scattering parameters, S11 and S21, the Nicolson-Ross-Weir algorithm can be implemented to explicitly solve for the permittivity [49, 108].
Using the reflection from the front surface of the material, $\Gamma$, and the transmission, $T$, is as follows:

$$\Gamma = X \pm \sqrt{X^2 - 1} \text{ where } X = \frac{S_{11}^2 - S_{21}^2 + 1}{2 S_{11}}$$

$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma}$$

With a third defined parameter, $\Lambda$, equal to:

$$\frac{1}{\Lambda^2} = -\left(\frac{1}{2\pi t} \ln T\right)^2$$

Permittivity can be solved for using,

$$\varepsilon = \frac{1}{\mu k_0^2} \left(\frac{4\pi^2}{\Lambda^2}\right)$$

Where the permeability, $\mu$, is one for non-magnetic materials and the wavenumber, $k_0$, is $2\pi/\lambda$ [49, 108].

There are other similar methods and algorithms by which to calculate the permittivity of planar materials. Keysight Technologies Materials Measurement Software uses a proprietary unpublished method referred to as Transmission Epsilon Fast, which is a technique that estimates the permittivity and iterates to minimize the difference between the scattering parameters calculated at that permittivity, and the measured values, until the error is below the expected system performance [109]. This method produced the most consistent results and yielded accurate measurements for known standards (such as varying...
thicknesses of Teflon and Rexolite). Figure 5.16 shows the calculated real and imaginary permittivity based on the transmission epsilon fast method.

![Nanotube Material Sheet Permittivity](image)

**Figure 5.16**: Permittivity (Real and Imaginary) as Calculated Using a Transmission Epsilon Fast Method.

The permittivity is a measure of a material’s ability to store energy within the presence of an electric field. It is related to the material real conductivity by:

\[
\varepsilon'' = \left[\text{Re}(\sigma)/\omega\varepsilon_0\right]
\]

Where \(\varepsilon_0\) is vacuum permittivity. The alternating current conductivity, \(\sigma\), can then be solved for [107]. The results are given in Figure 5.17.
Figure 5.17: The Calculated Sheet Conductivity of the Nanocomp Carbon Nanotube Material.

The alternating current conductivity values of the carbon nanotube sheet is around the expected values since they are the same magnitude, but significantly less, than ordered single walled carbon nanotube films. Minor fluctuations especially at longer length scales (i.e. around 4 GHz) can possibly be attributed to the gating used within the software, which relates to positioning of the front surface and the point at which reflections would be begin and end within the sample. Figure 5.18 shows the measured conductivity over a wide frequency band by Xu et al. for ordered single walled carbon nanotube thin films at several temperatures. The conductivity remains relatively constant, just over 2,000 S/cm, with temperature and frequency up until the onset frequency below 100 GHz [107].
Figure 5.18: Conductivity as Measured by Xu et al. for Thin Films of Single Walled Carbon Nanotubes at Varying Temperatures (Reproduced with Permission of AIP LLC) [107].

The conductivity calculated in this study follows the general trend of the conductance as measured by Bulmer et al. for an unsorted single walled carbon nanotube sample [28]. Neither have any noticeable overall trends in the sampled frequency range. Unsorted nanotubes are that which are not isolated by their chirality; both metallic and semi-metallic tubes are present [28]. The carbon nanotube shield material from Nanocomp Technologies is also unsorted. Multiwalled carbon nanotube bulk materials typically are, since adjacent layers are of different chirality within the nanotubes themselves [110]. Bulmer cites disorder playing a significant contribution in the conductance of the carbon nanotube samples, with junctions, defects, and lack of internal alignment all having negative effects [28]. The length of the nanotubes and the direct current conductivity also vary accordingly. This data is used to fit the extended pair approximation ($\sigma = \sigma_0 [1 + k \left( \frac{\omega}{\omega_0} \right)^s]$), while evaluating the disorder exponent. Multiwalled carbon nanotubes in polymer matrices are reported as having a disorder exponent between 0.94-0.93 [28]. It is likely that with the lack or alignment, amorphous nature, magnitude of junctions, relatively high density of tubes, and nanotubes with multiple walls, that the disorder exponent of the
shield samples measured in this study are close to one. Kilbride et al. discusses that with a disorder exponent of 0.8 or greater, but less than or equal to 1 and at frequencies less than 68 GHz, the charge carriers exhibit a hopping conduction mechanism due to disconnected or, likely in this case, weakly connected parts of a network (depictions of which are discussed in section 2.6) [37].

![Figure 5.19](image)

**Figure 5.19:** Conductivity of Single Walled Carbon Nanotube Films Around the 5 GHz Range [36] (Reproduced with Permission under the Creative Commons License).

These weak connections between networks can also determine how efficient the skin effect is for reflecting incoming radiation. Using the calculated conductivity from Figure 5.17 the skin depth can be determined.
Figure 5.20: The Calculated Skin Depth from 4 GHz to 18 MHz for the Planar Nanocomp Carbon Nanotube Material Sheet.

The skin depth ranges from about 24 nanometers to about 12 nanometers. This is much smaller than the values measured by Jarosz et al. and previously calculated in section 5.4.1.2., of 100 and 31.6 microns respectively [80]. This large discrepancy can be attributed to overall differences between planar measurements (with full coverage) and measurements of three dimensional shields with wraps, seams, connections, and apertures.

This skin depth measurement confirms as frequency increases, skin depth decreases and the material can block impinging fields over less and less thickness. This follows up until the field can penetrate at an off-set frequency, which correlates to the dimension of the largest seam or aperture. In this case, the shielding effectiveness peaks around 5 GHz for the carbon nanotube material shields despite the skin depth continuing to decrease. To
better utilize this low skin depth, a more uniform shield, or perhaps a more planar shield, is most beneficial. In addition, if the on-set frequency of the alternating current conductivity of the carbon nanotube material shield was measured and determined, a uniform shield would likely be significantly more efficient beyond that frequency. As conductivity rapidly increases, skin depth would decrease and shielding effectiveness would improve (without the presence of slits, apertures, etc.).

5.4.2 Metal Mechanisms

Figure 5.21 shows the adjusted shielding effectiveness of the cables containing metal braids. Overall the high frequency shielding of these cables is suitable (although dependent on the application). Silver and copper both conduct electricity exceedingly well and at about one gigahertz, silver has a skin depth of around 2 microns. With a plated thickness of roughly 1.5 microns of silver, this is about three quarters of one skin depth. Beneath silver is copper which at the same frequency has a skin depth of 2.06 microns. Estimating that there are about two skin depths between the copper and silver at 1 GHz, means that 86.5% of the external field is blocked. With a stranded braid formation, there is also extensive portions of overlap. This is why the shielding efficiency of these samples is more consistent with a slight steady increase. The skin depth is small because materials like copper and silver contain mobile charge carriers and therefore have high conductivity. Samples with a double braid have even more thickness of shield and more coverage so their shielding effectiveness stays consistently high throughout the range sampled.
Some of the cables, those with silver plated copper clad steel center conductors, started to show a small improvement around two gigahertz. This may be because the center conductor in those frequency ranges has a voltage standing wave ratio that begins to lower and stabilize as seen in Figure 5.9. The center conductor is more appropriately sending power in those ranges without as much loss or internal reflections within the conductor. The bare conductor receives and transmits more of the power in the field at higher frequencies. This is likely due to the skin effect pushing the signal charge carriers into the most conductive portions of the center conductor (the silver and copper) without limitations.

**Figure 5.21:** Adjusted Shielding Effectiveness of Cables with Traditional Metal
due to apertures or gaps. Since shielding effectiveness is measured now such that it shows the comparison of shielding effectiveness of the shields within systems, the shield is effectively blocking more power that otherwise would have been transmitted in this range.

At the highest frequencies, the silver-plated copper clad steel braided shields start to decline due to the presence of very small apertures within the braids. This is the case with all shields that are non-ideal and contain slits, holes, wraps, seams, etc. At some typically high frequency, the shield effectiveness drops off due to the small wavelength high energy field penetrating in through any possible openings and seams [106].

5.5 Mechanical Fatigue

Results of fatigue were slightly surprising. All samples were run from a peak load of fifty percent of the average ultimate tensile strength of the commercial RG-316 system to ten percent of the average ultimate tensile strength (from 32.8 lbf to 6.56 lbf). There were two ways in which samples could fail to withstand fatigue: The center line conductor or shield could separate indicated by either visual means or by sudden jumps in resistance measurements. Failure could also occur if the test fixture could no longer be supported by the conductor-shield system, typically due to elongation of the sample resulting in high displacement of the bottom grip. This is done largely to protect the experimental equipment as well as limitations of the test stand. The bollards begin to impact too harshly and risks breaking or causing severe damage to the rig if tests continue.

There were two types of systems that consistently failed during fatigue tests via elongation. These were the coaxial systems with silver plated copper clad steel center line conductors with one helical wrap of low density carbon nanotube tape, and silver plated
copper clad steel center line conductors with two helical wraps of low density carbon nanotube tape. Displacements measured well over an inch and sometimes over an inch and a half.

Additionally, the carbon nanotube yarn with a single layer of carbon nanotube tape system failed with the separation of the tape shield. This happened between 36 to 63 cycles depending on the exact cable.

Initial results seemed to indicate that there may be issues with the design of the carbon nanotube tape shields. The only system that did not result in failures of all systems with this shield type was the carbon nanotube yarn with the double wrap of the carbon nanotube tape shield (although some samples did elongate). This may have been because the carbon nanotube yarn center line lent support; also, the shield was a double layer which may have contributed extra strength. The carbon nanotube tape shields may have led to early failure since its construction is a helical wrap, which does not provide much axial support where as a construction such as a cylindrical braid may provide additional tensile strength. The helical wrap of the carbon nanotube tape likely behaves much like a stretched slinky; when pulled apart separation of the tape occurs and eventually the entire sample can yield. Samples with braided shields endured much better, which may have been due to the behavior of the braid akin to a Chinese finger trap. Applying a tensile load to the system allowed the braid to axially distribute the load and hold tight.

5.5.1 Displacement and Core/Shield Resistance Measurements

Utilizing displacement and resistance measurements collected during fatigue confirm initial observations. Samples such as the carbon nanotube yarn core with a double
braid of silver coated copper clad steel, in Figure 5.22, showed minimal displacement at fatigue and no breakage. Even samples with carbon nanotube yarn core and a single braid of silver coated copper clad steel showed no signs of breaking within their resistance measurements, shown in small fluctuations with cycling, as seen in Figure 5.23, with no major abrupt changes. There is very little displacement over the course of the entire fatigue.

**Figure 5.22:** Mechanical Fatigue Axial Displacement of Carbon Nanotube Yarn Center Conductor with Silver Coated Copper Clad Steel Double Braid.
Figure 5.23: Resistance Measurement of Carbon Nanotube Yarn Core with Single Silver Coater Copper Clad Steel Braid During Fatigue Shows Both Center Conductor and Outer Shield Remain Intact with Only Small Variations in Resistance.

Figure 5.24: Fatigue Cycling of CNT yarn Center Conductor with 2 wraps of CNT Shielding.
The same center conductor, carbon nanotube yarn, with a different type of shielding, a double wrap of carbon nanotube tape, however, has noticeably larger displacements and larger variations in displacements when peak load is applied. The sample does not break and endures the fatigue; however, it appears to be elongated even when minimal load is applied (between each cycle).

![Fatigue Cycling - T4S2](image)

**Figure 5.25**: Fatigue Cycling of Silver Plated Copper Clad Steel Center Conductor with a Double Braid of Silver Coated Copper Clad Steel.

This sample, of silver plated copper clad steel core and silver coated copper clad steel double braid shows similar displacements to the previous sample with the same braid but a carbon nanotube yarn center. The double braid seems to allow for little elongation and helps support the load. It is confirmed that both the center conductor and the outer shield stayed intact, seen in the in-situ resistance measurements in Figure 5.26. Both core and shield show relatively minor changes in resistance over the course of the fatigue with
no major changes. Comparing displacements and resistance evidence of where breaks occur, suggests that the samples with a plated steel core are enhanced by the mechanical support of the silver coated copper clad steel shield braid.

**Figure 5.26:** In-situ Resistance Reading during Fatigue Shows Little Variation in Resistance indicating both Silver Coated Copper Clad Double Braid Shield and Silver Coated Copper Clad Steel Core are Intact.
Figure 5.27: Silver Coated Copper Clad Steel Center Conductor with Double Wrap of Carbon Nanotube Shield Showing Large Displacements During Fatigue.
Figure 5.28: In-situ Resistance Reading During Fatigue Shows breakage of Carbon Nanotube Wrap Shield Where the Resistance Rapidly Jumps Indicating Shield Separation.

During fatigue, the same silver-coated copper clad steel center conductor, but carbon nanotube tape shield, cable begins to break. As seen in Figure 5.28, the extraordinary large jump in resistance seen in the shield suggests that part of the shield has separated. The displacements in Figure 5.27 show higher displacements, with values exceeding an inch. These in-situ measurements are substantiated by post fatigue analysis.

5.5.2 Material Fatigue Analysis

5.5.2.1 Microscale Fatigue

Scanning electron microscopy was performed to determine if any fatigue or damage occurred on the microscopic level for each material. Samples were taken from the very
center length of the most fatigued cables in hopes of detect any damage. These samples were compared to small samples of pristine material.

For the most part, fatigue was near undetectable for most samples. In the case of silver coated copper clad steel virtually no fatigue is noticeable even at high orders of magnification (as high as about 1000x) as seen in Figure 5.29.

Figure 5.29: Silver Coated Copper Clad Steel Shield Pre-Fatigue (left) and Post Fatigue (right)

Zooming out, to about 400x the magnification, damage is no more evident. At the most the copper becomes detectable underneath the silver, where strands slide past one another. This small feature however is present both in the fatigued and unfatigued sample as seen in Figure 5.30.
The carbon nanotube centerline yarns, on the other hand, did show slight signs of fatigue. Fraying is noticeable at around a 400x magnification. It appears that edges that were in contact with other yarns began to slough off to some extent. For the most part, there is not much breakage, and the yarn is otherwise fully intact.

**Figure 5.31:** Carbon Nanotube Yarn Center Conductor Pre-Fatigue (Left) and Post Fatigue (Right).
For the carbon nanotube tape shield detecting fatigue was challenging. A different voltage, and therefore spot size, was used between scopes (which explains the difference in image size and contrast). There was very little evidence of stretching or fracture or any other sign of mechanical fatigue in the post-fatigue sample.

![Carbon Nanotube Tape Shield Pre-Fatigue (Left) and Post Fatigue (Right).](image)

**Figure 5.32:** Carbon Nanotube Tape Shield Pre-Fatigue (Left) and Post Fatigue (Right).

Similarly, the carbon nanofiber shield made by ASI showed little evidence of fatigue as well. The texture remained overall the same between pre and post fatigue samples. There were no signs of stretch or particular fraying, as can be seen in Figure 5.33.
Using scanning electron microscopy did not provide much evidence of fatigue on the material/microscopic level. There did not appear to be any noticeable stretching, breaks, fractures or distortions. It was worthwhile to look however, as previous studies have shown strong signs of tensile testing/fatigue on the microstructure level, affecting electrical properties [94, 100].

5.5.2.2 Fatigue of Architecture

After not observing evidence of fatigue on the micro-scale, it is important to look at the general structure of each cable. When looking for evidence of fatigue, looking at the actual cable it is obvious something is different about them. Most of the cables have elongated and stretched, emphasizing the effects of strain. In many instances, the cross-sectional area of the cable has dramatically reduced post fatigue.
Figure 5.34: Average Post Fatigue Percent Elongation of Each Cable Type.

Figure 5.34 shows the average elongation experienced for each prototype conductor-shield combination. As seen, the highest elongation and plastic deformation is seen for the samples that failed during fatigue, the silver-plated copper clad steel with one and two wraps of carbon nanotube tape.

The average reduction of cross sectional area for the most elongated cable, silver plated copper clad steel with one wrap of carbon nanotube tape, and the second most elongated cable, the same center conductor with one wrap of carbon nanotube tape, was roughly 52% and 55% respectively. These cables show strong evidence of a more ductile deformation. This may have been encouraged by the helical architecture of the carbon
nanotube tape shield. The shield deforms more similarly to a stretched out slinky, rather than uniaxial bearing the load of the cable.

These changes indicate the effect each material component has on the mechanical integrity of the system. With a sample size of only three per each cable type, and a couple cables having been misplaced by the mail, it may be difficult to make fine distinctions. It appears the most durable design is that of a carbon nanotube yarn with a double braid of silver plated copper clad steel. Given the center conductor, carbon nanotube yarn, has demonstrated ultimate tensile strengths over 2 GPa [90], and shield braiding that acts akin to a Chinese finger trap (likely tightening with tension and axially distributed the load), this combination may make the most mechanical sense. This cable type experienced the least elongation/deformation and did not fail any of the fatigue tests. If a carbon nanotube tape shield was desired, in order to ensure mechanical stability and little deformation, incorporating a carbon nanotube yarn center conductor would be most mechanically beneficial.
Cables were inspected post fatigue for signs of mechanical degradation using nondestructive evaluation of x-ray radiography. The field, current, and duration are varied according to how conductive the sample is to achieve proper contrast. In some of the samples, particularly the samples containing both carbon nanotube based materials and silver plated copper clad steel, it was a challenge to be able to distinguish both shield and center conductor. In the sample above, in Figure 5.35, both the center conductor and shield of silver plated copper clad steel, are discernable and clearly show little to no signs of mechanical fatigue.
Figure 5.36: X-ray Image of Carbon Nanotube Yarn Center Conductor with Double Metal Braid

Besides the sample label on the left towards the cable connector, the cable in Figure 5.36 shows little overall signs of fatigue. There are some slight variations seen with the braids tightness. This could be due to the manner in which the sample was secured using the bollard grips, allowing for sections towards the middle to slightly stretch and tighten the braid, while sections toward the grips show more signs of bending/turning with slightly looser portions of the braid being towards the connectors. It’s very possible this could also be due to overlay of two shields.
With a single braid of shield, less contract is needed to probe, however detecting the carbon nanotube yarn center conductor becomes challenging, as seen in Figure 5.37. The same slight variations in braid tightness exist (label is observed on the left side towards the connector), with some small loosening of the braid occurring towards the connector. Most discontinuities with the center conductor are likely undetectable within this arrangement. This shows no sign of any significant breaks overall and the shield is complete, with comprehensive coverage throughout and no major bends or breaks.

**Figure 5.37:** X-ray Image of Carbon Nanotube Yarn with Metal Braid
Figure 5.38: Various Changes in Coverage of Silver Coated Copper Clad Steel Single Braid, Post Fatigue.

Figure 5.38 shows the large variation of the braid shielding on the cable (all the same shield). In some sections, the braid has tightened. In other sections, it appears winding the cable around the bollard grips has loosened portions of the braid and apertures are more apparent.

These lose sections were measured using a calibrated Dino Lite Digital microscope that was calibrated using known length standards. The largest dimension (for most rectangular or rhomboid shape opening, the diagonal) of any aperture measured was 6.284 millimeters. The average longest dimension measured 3.455 millimeters. Typically for design purposes it is recommended that twice the largest dimension of any aperture be less than $1/20^{th}$ of the smallest wavelength encountered so that no interference can penetrate [111]. In this case, for an aperture with the largest dimension of 6.284 mm that correlates to a frequency of 1.09 GHz, which is quite low. For the average 3.455 mm dimension that would correlate to a cutoff frequency of about 2.2 GHz.
Not all of the x-ray images showed the conductor or shield staying undamaged. In samples that failed during fatigue or showed significant elongation, manifestations of fatigue showed. In Figure 5.39, of a carbon nanotube yarn center conductor with a single wrap of carbon nanotube tape shield shows where the carbon nanotube tape helical wrap has begun to stretch out. Due to the separation, which in-situ resistance measurements during fatigue have confirmed, the individual sections of wrap are now apparent. Although there are no large tears or breaks, this shows the shielding is starting to come apart. After deconstructing several cables post fatigue, Figure 5.40 confirms the separation of the carbon nanotube tape wrap separation of the first wrap within a double wrapped cable.
Figure 5.40: Carbon Nanotube Tape Wrap Separation.

Figure 5.41: Carbon Nanofiber Shield Separation from Connector.
In some samples, the evidence of fatigue is much more obvious. Figure 5.41 is actually quite important as it relates to the unique antenna-like effects seen in the shielding effectiveness. This depicts the difficulty of forming a proper termination in the cables that are composed of carbon nanotube materials. When the shield is not grounded and/or completely detaches from the connector, the shield is still conductive and stores charge, except the charge does not flow as easily to ground. When the charge builds up on the shield without being grounded, the signal gets coupled into the center conductor acting like an antenna. This appears as a negative shielding effectiveness in the developed technique. This termination difficulty occurs often in other types of shields, such as aluminum wraps, which have higher resistance and are hard to form a proper connection with ground; they are also difficult to solder. To help mitigate this issue, a drain wire is typically employed in these circumstances in contact with the length of the shield on the most conductive side and terminated with a crimped connection [106].

Figure 5.41 shows the complete detachment of the shield of a carbon nanofiber wrap shield from the connector around a silver-plated copper clad steel conductor. It appears that cables with carbon nanotube/nanofiber shields or conductors sometimes do not adhere to the connectors as well. This could be due to a poor connection using the silver Loctite. In fact, other x-ray images depict the messy nature of the Loctite with small splotches. This is the most drastic separation of a shield or conductor in x-ray images, though it is seen in other samples with a carbon nanofiber shield. In addition, other samples did have a connector that came apart, such as a carbon nanotube yarn center conductor with a single braid of silver plated copper clad steel. With the complete removal of shield from connector on one side a faraday cage is no longer formed and the signal within the cable is
no longer as protected. The ramifications of this fatigue can be seen in the post fatigue high frequency shielding effectiveness measurements.

5.6  Post-Fatigue Conduction Characterization

Figure 5.42:  Copper Core with Copper Braided Shield Characterization.
Figure 5.43: Copper Core with Double Carbon Nanotube Wrap Shield Characterization.
Figure 5.44: Carbon Nanotube Core with Copper Shield Characterization.
Post fatigued characterizations shown are for the same samples that were shown for pre-fatigued characterizations.

Mechanical fatigue clearly had an effect on all the samples. The least effected were the traditional copper center conductor and braided copper shield. Impedance rose only slightly and for the most part it appears the systems stayed intact. The insertion loss rose almost unnoticeably and overall the system does not seem much different than it was pre-fatigue.

The copper conductor with two layers of carbon nanotube tape shield (Figure 5.43) shows a large effect due to fatigue. The real impedance about doubled, reaching around

**Figure 5.45:** Carbon Nanotube Conductor with Double Layer Carbon Nanotube Shield.
200 Ohms, which is undesirable for a 50 Ohm system. It appears as though there are many discontinuities in the conductor as the return loss is rather noisy and high. In addition, the insertion loss increases, meaning more signal is attenuated (i.e. lost) down the system post fatigue.

The carbon nanotube conductor samples preformed the worst but this may also be because even pre-fatigue, characterizations showed these cables underperform compared to their metal counterparts in most regards. For both carbon nanotube based conductor systems, with copper braided shields (Figure 5.3) and with double layers of carbon nanotube tape shields (Figure 5.4), there was some increase in the already quite high impedance. It’s no surprise that the cables with the conductors and shields of the highest impedance, overall higher voltage standing wave ratio and relatively high insertion loss are not exactly the most impressive in those regards after fatigue. Add to that, the poor connection to the SMA connectors and a carbon nanotube wrap shield that has begun to separate allowing signal to leak at higher frequencies; what’s left is a pretty poor transmission of signal.
Figure 5.46: Changes in Attenuation/Insertion Loss Pre-and-Post Fatigue.

Figure 5.45 shows the changes in attenuation due to fatigue. This emphasizes the overall trends from lower to high frequency of the four selected cable types pre and post fatigue. The cable type with the least change in attenuation due to fatigue is the silver plated copper clad steel with a double braid of silver plated copper clad steel; this cable had virtually no change in attenuation. The other cable with the same center conductor, silver coated copper clad steel, experienced further attenuation, or loss of power due to fatigue. This may be because its shield was carbon nanotube tape wrap and therefore it did not have the axial support of the braid to mechanically reinforce the cable during fatigue. Without a strong shield, the shield may have begun to come apart as shown in its high elongation.
This would lead signal running down the cable to have more opportunity for egress and leak out because the center conductor is no longer as protected by a faulty shield. In addition, it is possible that with a weaker shield, the center conductor began to mechanically degrade itself. Interestingly, both carbon nanotube yarn center conductor cables showed some signs in improvement of signal loss after fatigue for the samples shown. While the carbon nanotube yarn with the metal braided shield only improved slightly, this could be because with the support of the concentric braid during fatigue. The carbon nanotube yarn did not have to support as much of the load during fatigue. It appears fatigue improves conductivity of carbon nanotube yarns in some instances.

**Figure 5.47:** Changes in Conductivity for Fatigue Cycling of 60 and 100-Yarn Wire for 50% (a and b) and 60% (c and d) and 75% (e and f) of the Ultimate Tensile Strength (Reproduced with Permission of 2013 Elsevier) [94].
Misak et al. shows for carbon nanotube yarns (in this study, of sixty and one hundred plies) that conductivity improves with increasing fatigue all the way up to 75% of the ultimate tensile strength. They cite the reasoning for this as a reduction in voids between strands with fatigue. In addition, the contact between strands of nanotubes decreases with fatigue and therefore overall resistance reduces [94].

**Figure 5.48**: Strain Induced Alignment of Carbon Nanotubes. SEM Images of Multi-Walled Carbon Nanotube Networks at Strains of (a) 0%, (b) 10%, (c) 20%, and (d) 30% (e and f are Resin Treated) (Reproduced with Permission of 2014 Jon Wiley and Sons) [100]
Downes et al. also found similar alignment results of amorphous multiwalled carbon nanotube sheets. Using a uniaxial load, Downes et al. was able to induce ductile formation and, as they described it, strain hardening, of similar materials to this research study (akin to the carbon nanotube wrap within shields). They noticed improved alignment of the multiwalled tubes post strain as seen in Figure 5.48. This behavior could improve in plane conductivity of either the multiwalled carbon nanotube yarn or the carbon nanotube tape within cables. However, this effect would be much more applicable on a cylindrical wrap as opposed to the helical wrap used.
5.7 Post-Fatigue Shielding Effectiveness

**Figure 5.49:** Post Fatigue Low Frequency Baseline Comparison Preliminary Results.
Figure 5.50: Post Fatigue High Frequency Baseline Comparison Preliminary Results.

These preliminary results of the post fatigue shielding effectiveness measurements highlight the need for an improved measurement system. It should be noted that the post-fatigued shielding results are shown for the same sample set as the pre-fatigue shielding results.

All data is shown for the baseline comparison method utilizing an unfatigued copper baseline. Fatigued baselines are incorporated into adjusted shielding effectiveness measurements.
The carbon nanotube conductor and single layer carbon nanotube shield sample with unusually high shielding in the low frequency shielding effectiveness results in Figure 5.49 indicated a break within in-situ fatigue measurements and within post fatigue cable characterizations. This emphasizes why using a similar baseline comparison is necessary. In addition, the negative dip seen in the low frequency tests at around 100 MHz is likely an artifact of either the cable lengths or limitations of the injection probe used.

Overall thicker carbon nanotube and nanofiber shields appear to excel better in the highest frequency ranges both pre-fatigue and post-fatigue. These measurements highlight the need for a method that incorporate broken, damaged, or high impedance center conductors. This is particularly necessary since physical fractures in the system’s conductor may overinflate shielding data and/or may mean the system is no longer impedance matched to the load it was tested with.
Figure 5.51: Corrected Post Fatigue High Frequency Baseline Comparison Results.

Figure 5.51 shows the adjusted shielding effectiveness for each cable type. With the adjusted method, there is not as drastic of a decline in shielding effectiveness for the metal shielded cables. This may be because shield effectiveness is lower as a whole, dropping down to about 40-50 dB rather than 60-70 dB for some of the more shielded samples. In addition, the increase for the carbon nanotube tape shields is slightly subtler. Part of the reason this could be is that this method accounts for the signal carrying capability of center conductor now and if that has declined due to fatigue or if that has improved even due to fatigue then this measurement will account for such changes. In
addition, one sample of the sort shows practically no shielding effectiveness which may be expected due to the broken shield.

Some of the samples with silver plated copper clad steel braids do show the slight decline in shielding effectiveness around 2 GHz which was predicted in section 5.4.1.2 based on the dimensions of the braid apertures.

![Shielding Effectiveness - Reverb Method](image)

**Figure 5.52:** Changes in High Frequency Shielding Effectiveness Post Fatigue.
Looking at the difference fatigue makes on the shielding, Figure 5.52 shows the changes for each cable type in shielding effectiveness from pre to post fatigue. Most of the changes are somewhat subtle although a couple small trends stand out. The cable type that elongated the most and failed during fatigue, had the biggest decline in shielding effectiveness. Fatigue resistance tests showed the break to have occurred within the shielding. In addition, the helical wrap showed separation in x-ray images post fatigue as well as in deconstruction pictures. It is likely the separation of the wrap is responsible for the major decline in shielding effectiveness around 4-5 GHz. There was also a shift in the carbon nanotube tape shield cutoff frequency. Since the frequency at which interference begins to penetrate is dependent on the largest dimensions of any openings or apertures, the apertures, in this case, increased in size with fatigue. With the helical wrap stretching with the length of the cable during tension, this means that the wrap began to come apart more.

The commercial RG-316 comparison sample showed some signs of improvement post fatigue towards 1-2 GHz. This is likely due to the braid of the shield tightening due to fatigue, reducing any apertures of larger sizes present and increasing coverage. This may not have occurred in prototype samples as commercial cabling had high conformality and tighter heat shrink. This may have supported any bending that occurred during fatigue and made the cable a bit more resilient to flexure and fatigue.

Stretching in other samples, particularly with wraps, and the subsequent reduction in cross section, could have densified and brought shielding into tighter contact. This might be the case for the slight improvements of the metal center conductor with one wrap of carbon nanotube sheets.
Overall not many over-riding trends are derived from the changes in shielding effectiveness due to fatigue. Changes vary by frequency with subtle increases and decreases. Part of this may the result of the grip style used during fatigue as well as poor connectivity and terminations in some of the cables. It is clear however that fatigue induced larger separations of shielding, which does negatively impact shielding effectiveness.
Carbon nanotube yarn, carbon nanotube tape, and carbon nanofiber tape were constructed into professionally manufactured coaxial cable prototypes. Cables consisting of silver plated copper clad steel center conductors and braided shield were used as a standard of comparison.

All cables were swept on a vector network analyzer and important transmission properties calculated, including insertion loss, voltage standing wave ratio, impedance, and reflection coefficient. Many of the novel cables suffered from higher insertion losses however none of the cables preserved the fifty-ohm impedance across all frequencies. The signal carrying capability was analyzed across a wide frequency.

Many measurement methods used to quantify the ability of three dimensional shields to protect signal were studied but were inadequate to incorporate the differing aspects of novel materials, such as carbon nanotube and nanofiber tapes and shields, within coaxial geometries. A new measurement method was necessary to integrate impedance mismatches and the reduction of attenuation due to the addition of the shield (which otherwise gets lumped into the effectiveness of the shield). Using the voltage standing wave ratio, which is a gauge of how well matched a system is, as a normalization shows
how well shielded the system is and not just each planar part at a narrow frequency band. This method assesses the susceptibility of these novel materials, or any material, as a part of complex system and how well protected signal may be within a high frequency field.

Shielding effectiveness was measured and corrected using the proposed normalizations. Differences were observed and measurements incorporated unique mechanisms such as antenna like behavior of shields, and transmission abilities of center conductors. Shielding of the carbon nanotube material was further examined by using a focused beam and reflection, transmission, and absorption fractions were calculated, revealing that the carbon nanotube sheet reflected nearly all the incoming power. The electromotive force of the skin effect allowed for an increase in mobile charge carriers at the surface, allotting for efficient reflection towards 5 GHz.

Each system was then mechanically fatigued. In-situ measurements were used to determine if and where each cable system failed. Systems with carbon nanotube tape shields and metal center conductors fared the worst and also showed the highest plastic deformation. The helical wrap of the carbon nanotube tape did not axially support the load, much like a braid would, and began to stretch and come apart. With a carbon nanotube yarn center conductor, samples remained more intact because of the yarn’s high tensile strength. The single and double braided metal shields functioned well mechanically as they could axially support the load. X-ray images, microscope images and pictures confirmed initial findings of fatigue within the architecture and showed little evidence of mechanical fatigue on the microscopic level. Helical wraps began to separate and SMA connections to carbon nanotube/nanofiber materials came apart. Utilizing a drain wire in addition to carbon nanotube based shields may be helpful in future work or finding a better connection.
between metal connectors and carbon. Additionally, if flexure tolerance is not a concern employing a cylindrical wrap of a carbon nanotube sheet may provide better mechanical support.

Fluctuations in braid apertures were observed and connected to shield offset frequencies. Future work could entail systematic stretching of apertures to shift frequencies of decline in shielding effectiveness.

Post fatigue signal characterization and shield effectiveness measurements were repeated and changes observed. Attenuation of signal due to fatigue was calculated. Shifts in shield offset could be attributed to changes in aperture dimensions due to fatigue. Any improvements of carbon nanotube conductors or possibly shields could be due to stretch and densification of tubes. For future work, it may even be beneficial to stretch center conductors of carbon nanotube yarn prior to assembly to improve conductivity due to densification and strain hardening.

The most significant contribution this research makes in an improved measurement method to comparatively analyze the high frequency coaxial system susceptibility of novel (or even traditional) materials within coaxial geometries.
CHAPTER 7
CONCLUSIONS

Carbon nanotube materials are often studied for the electrical and low-density characteristics. A very common application of such materials is employing them as a conductor and/or shield within coaxial cables. When such studies are done however, measurements made on the shield are either from an attenuation standpoint or are shielding measurements of a planar sample at a narrowband of frequencies.

Shielding measurements on such prototypes are challenging to make. Most traditional methods fall short of capturing the behavior of the novel system. Three-dimensional geometry, including seams, apertures, and non-uniformity, is overlooked in many techniques. Reverberation chambers make for a robust testing environment due to their: representation of complex real-life environments, excited fields that incorporate all aspects angles with any possible polarization or phase, and their repeatability of measurements.

While a reverberation chamber shielding measurement method is highly practical, it does have pitfalls when testing cabling that incorporates novel materials, such as non-metals. This study has shown since carbon nanotube bulk materials have low and variable conductivity in the presence of alternating current, that carbon nanotube based cables’
characteristic impedance response can be inconsistent across the tested frequency range (and higher than the system design). This is even the case in some traditional metal samples. Shielding tests, like the one in this research, operate on the principal of a constant power being delivered to a set load through the cable. If the transmission is inconsistent, due to fluctuating characteristic impedance, then shielding effectiveness results are inaccurate.

This research developed professional coaxial cables that were comprised of both metal and carbon nanotube and nanofiber materials. Cable characterizations on a network analyzer were performed not only to assess the attenuation and transmission of each cable set (as well as bare center conductors), but to use as a common point of reference for shielding effectiveness measurements.

A novel approach was established that normalized high frequency shielding effectiveness using the voltage standing wave ratio for each cable as well as for a bare center conductor. This allowed for a more accurate depiction of the shield behavior within the coaxial system in a high frequency, randomly polarized field.

Using this approach, carbon nanotube shields showed improved shielding capability towards 5 GHz. This was determined to be due to the skin effect and an accompanying focused beam measurement indicated a reflection mechanism. The helical nature of the carbon nanotube shields however did not perform well during mechanical fatigue. For this reason, a carbon nanotube tape shield would not be recommended for applications experiencing tensile loads, such as high-tension transmission lines, nor would it be advisable to use integrated into systems that undergo thermal expansion and cycling.
Traditional metal braids would be advisable in those conditions due to the axial support and tight braid.

A carbon nanotube wrap shield would be best served in applications such as communication lines which need to be uninterrupted by nearby wi-fi or radio signals running around 3-6 GHz, in situations where weight really matters. This could include situations such as satellite or transportation, where weight is highly important and the cabling remains relatively stationary with minimal tension.

This process by which to evaluate coaxial systems, however, can be used to validate and ensure the fidelity of cabling, that employs virtually any material (pristine or fatigued), both for signal transmission and for shielding efficiency within high frequency electromagnetic fields.
REFERENCES


