Carbon Nanotube Low Voltage Differential Signal Cables for Space Applications

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ABSTRACT

TE Connectivity has produced cables that utilize Carbon Nanotube (CNT) materials for shielding and/or conductor. An all CNT prototype space bus cable has been constructed and demonstrates similar 1553B Word Test results as a standard copper construction with a 69% weight savings. Low voltage differential signal cables have been tested at 1MHz and 10MHz with a differential square wave input; the all CNT cable provides a 65% weight reduction with acceptable signal loss.

INTRODUCTION

During the late 1990s and for most of the first decade of the 2000s, there was significant research in academia and by industry on Carbon Nanotubes (CNTs). CNTs are a low density cylindrical allotrope of carbon made of one or more layers of graphene. Due to their unique aspect ratio and quasi one dimensional nature, CNTs exhibit unusual physical properties: electrical conductivity greater than silver, tensile strength greater than steel and thermal conductivity greater than diamond. CNTs have been investigated for use in a myriad of applications including sensors, actuators, microelectronics, energy storage, water purification, and medical devices [1]. Despite these efforts, there are currently few successful products using CNT; high strength composite structures are arguably the first commercial win. CNT cost and limited volume availability have restricted introduction into existing markets - though cost is decreasing rapidly as manufacturers increase volume capability.

One candidate market for near-term CNT introduction is Space. With low-earth orbit launch cost of at least 12.5k USD per kilogram for CubeSats, the possibility of replacing copper based wiring and shielding with a material that is eighty-four percent less dense can create viable costs and size savings. This market can be expanded to the greater Aerospace, Defence, and Marine (AD&M) sector where the key technology drivers are reduced Size, reduced Weight, and increased Power, denoted by the acronym SWaP. We address CNT wire and cable relevance for Space and AD&M applications in this paper.

MATERIAL TYPES AND CHARACTERIZATION

Commercially available materials were obtained for substrate-based testing as well as cable prototype builds. The formats, manufacturer, materials, and application are listed in Table 1. Vendor names have been anonymized. CNTs are manufactured via high temperature processing, such as chemical vapor deposition, arc evaporation or laser ablation. Growth parameters such as temperature, reactor chemistry, and catalyst affect the resulting CNT in terms of length, diameter, physical structure, electrical behaviour (metallic or semiconducting), and mechanical strength. The methods of agglomeration of CNTs into macroscopic formats also vary among manufacturers, such as entangled networks, aligned fibres, or substrate interaction [2].

Table 1. Material Types and Applications

<table>
<tr><th>Format(s)</th><th>Manufacturer</th><th>Materials</th><th>Application</th></tr>
<tr><td>Yarn</td><td>US Vendor A</td><td>CNT</td><td rowspan="3">Centre Conductor</td></tr>
<tr><td>Fibre</td><td>EU Vendor B</td><td>CNT</td></tr>
<tr><td>Fibre</td><td>EU Vendor C</td><td>CNT</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>Tape</td><td>US Vendor A</td><td>CNT</td><td rowspan="5">Shielding</td></tr>
<tr><td>Fibre</td><td>US Vendor D</td><td>CNT/Glass Fibre
CNT/Carbon Fibre</td></tr>
<tr><td>Sheet</td><td>US Vendor D</td><td>CNT Composite</td></tr>
<tr><td>Sheet</td><td>US Vendor E</td><td>CNT</td></tr>
<tr><td>Tape</td><td>US Vendor F</td><td>CNT</td></tr>
</table>

Powder	US Vendor G	CNT	

These materials were tested via the methods listed in Table 2. Electrical conductivity is the key parameter for centre conductor material. Shielding materials need to be conductive to block electromagnetic radiation but much less so than the signal carrying component. The critical parameter for shielding material is mechanical robustness for introduction into the existing wire and cable manufacturing factory without retooling, limiting capital equipment expense and process development costs.

Table 2. Material Characterization Testing

Test	Format	Metric of Interest
Raman Spectroscopy	Yarn, Fibre	Carbon Nanotube Structure
Thermogravimetric Analysis	Yarn, Fibre	Composition
Scanning Electron Microscopy	All Formats	Morphology
Electron Dispersive Spectroscopy	All Formats	Composition
Tensile Strength	Yarn, Fibre	Mechanical Properties
Tear Strength	Tape, Sheet	Manufacturability
Conductivity	Yarn, Fibre	Electrical - DC
Impedance	Yarn, Fibre	Electrical - AC
Shielding Effectiveness	Sheet	Electromagnetic Interference Shielding

Raman spectroscopy was used to identify the number of walls in the tubes and their purity by examination of the G, G,' and D bands. Most materials screened were dual or few walled though both single and multi-walled CNTs were also observed. Thermogravimetric analysis (TGA) was used to quantify material purity and determine the amount of residual growth catalyst present. The tensile and tear strength tests were used to determine suitability for automated equipment processing. Scanning electron microscopy (SEM) created qualitative images of the macroscopic CNT material morphology, as shown in Fig 1. Field emission SEM was used to resolve nanotube bundles at high magnification. Electron dispersive spectroscopy (EDS) was used to identify the chemical composition of any defects observed during SEM.

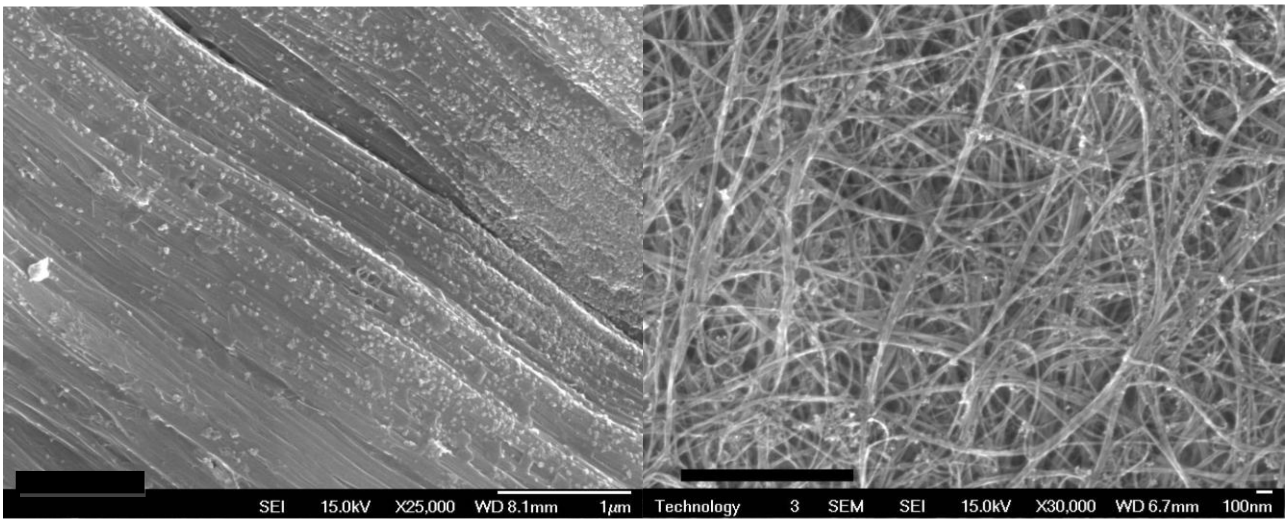


Figure 1: Electron Micrographs of CNT macroscopic material by two separate manufacturers. The sample on the left is aligned; the sample on the right has a highly entangled random orientation.

Note the alignment of the CNT bundles in the left image versus the bundles visible the right; alignment, along with other physical structure characteristics such as chirality, defect density, CNT length and CNT bundle length can correlate to both mechanical and electrical performance.

SHIELDING EFFECTIVENESS

The materials listed in Table 1 were submitted to a high frequency (1 to 8 GHz) electromagnetic shielding test, adapted from ASTM D4935. Several standard shielding materials, including copper braid and metalized fabrics, were used for comparison. Shielding effectiveness (SE) values in dB are listed at 4 GHz in Table 3.

Table 3. Shielding Effectiveness at 4 GHz

Format	Manufacturer	Material	Areal Density (g/m^2)	SE (dB)
Metallic Over-Braid	**TEC**	**Copper**	**3500**	**50**
Metalized Polymer Braid	Competitor A	Metal/Polymer	585	40
Metalized Fabric 1	US Vendor H	Ag/Nylon	125.5	60
Metalized Fabric 2	US Vendor I	CuNi/Polyester	68	68
2 layer CNT Sheet	**US Vendor A**	**CNT**	**40**	**52**
CNT Buckypaper	TEC/Vendor G	CNT	35	58
1 layer CNT sheet	US Vendor A	CNT	19	44
CNT spray coating	TEC/Vendor G	CNT	0.8	27

The nanomaterials exhibit comparable high frequency shielding effectiveness at low areal densities. The bolded data highlight traditional copper metallic over-braid and 2 layers of CNT sheet. Both the metal and CNT have the same approximate shielding effectiveness (~ 50dB) but the CNT material is over ninety eight percent lighter in weight. Buckypaper performed slightly better than the CNT sheets but is not available at large volumes and is not sufficiently robust.

At low frequencies (< 100 MHz) CNT material shielding effectiveness begins to degrade; this is due to CNT high resistance compared to copper. The most conductive CNT materials tested were 10x more resistive than copper; the least conductive CNT materials were 1000x more resistive. Hybrid constructions of CNT and metal extend the low frequency range with moderate weight increase and will be discussed later in this paper.

MIL STD 1553B PROTOTYPES

CNT twisted pair cables were built for comparison to copper MIL STD 1553B cables. The cables were built using 26 AWG equivalent diameter CNT yarn upon which an ethylene tetrafluoroethylene (ETFE) layer or fluorinated ethylene propylene (FEP) was extruded. The insulated yarn was constructed into a twisted pair cable; a single layer of CNT tape was then hand wrapped as the shielding material. A final jacket of ETFE was then extruded on the assembly. A stripped cable is shown in Fig. 2.

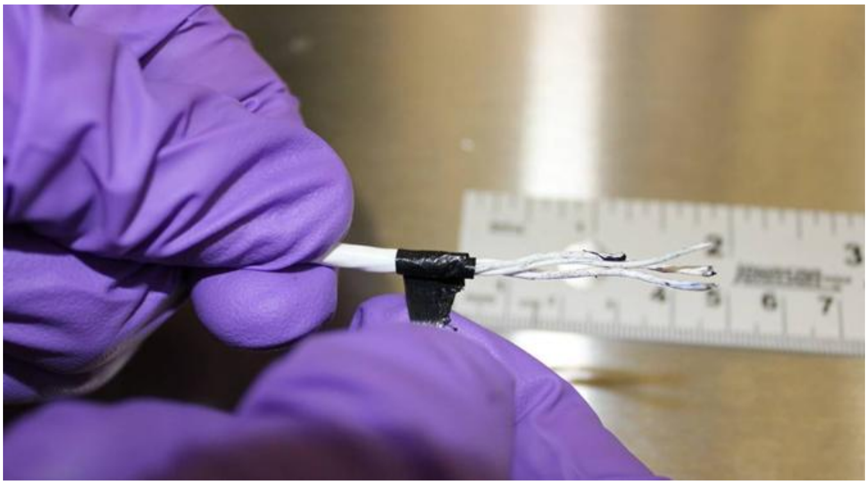


Figure 2: Engineer holding stripped CNT Cable. The ETFE coated CNT wires are visible on the right side of the image. The ETFE jacket material has been stripped revealing CNT tape shielding.

The weight reduction by substituting CNT for copper was sixty-nine percent as shown in Table 4 and examples of each cable listed are shown in Fig 3.

Table 4: Various Twisted Pair Cable Constructions

Cable Type	Linear density (g/m)	Weight Reduction
Standard copper construction, ETFE insulation	26	--
Copper conductor, CNT shield, ETFE insulation	15	42%
CNT Conductor, CNT shield, FEP insulation	8	69%

c

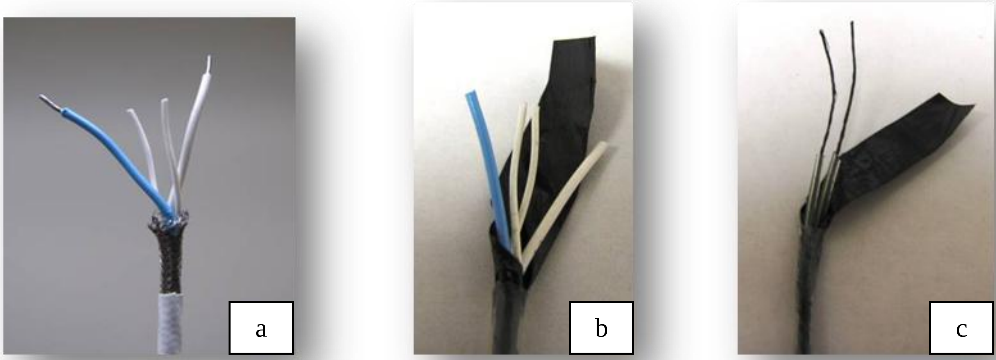


Figure 3: (a) Standard copper construction; (b) copper centre conductor with CNT tape shield, (c) All CNT construction with FEP insulation

A comparison between the standard copper and all CNT cable during a 1 MHz Word test of 4m cables showed a 12.955V drop for the copper databus and a 13.067V drop for the all CNT (i.e. 13V for each.) Screen captures of the test are shown in Fig 4. The lower half of each screen shot is the input signal and the upper half is the output signal,

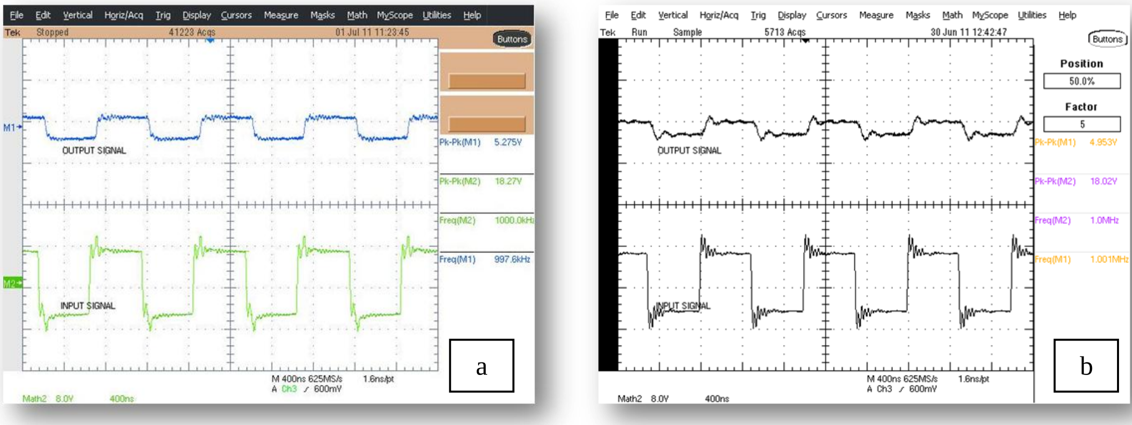


Figure 4: Word Test on 4m cables (a) standard copper (b) all CNT. Voltage drop is 13V.

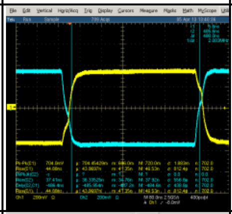
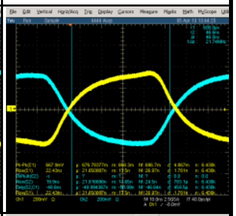
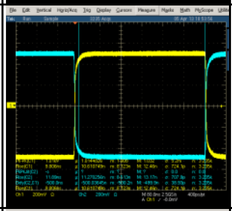
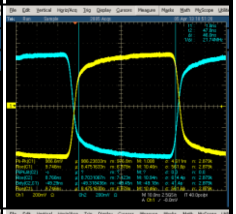
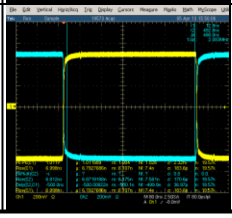
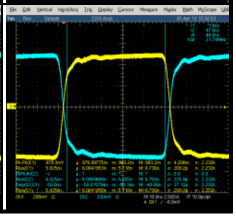
LOW VOLTAGE DIFFERENTIAL SIGNAL PROTOTYPES

In a second series of experiments, low voltage differential signal (LVDS) cables incorporating CNT materials were built in our laboratory in Menlo Park, California; in order to rule out performance differences due to construction on prototype (non production) equipment we also built the copper control cable for the experiment. The cables are pictured in Fig 5.

Figure 5: Three cables manufactured in the prototype laboratory - (a) CNT conductor/CNT tape shield; (b) Cu Conductor, CNT tape shield; (c) Cu conductor, Cu braid shield

The cables underwent a pseudo eye pattern test; a differential square wave input of a 5ns rise time at 1MHz and 10MHz. The cable output waveforms were captured on an oscilloscope (Table 5). The all CNT cable exhibits a decrease in the peak to peak voltage consistent with the increase in resistance due to the CNT centre conductor; note there is no perceivable difference in peak to peak voltage for the copper centre conduct/CNT tape shield construction. The pseudo eye pattern shape is unchanged at 1 MHz; there is a slight narrowing for the Cu conductor/CNT tape shield construction and increased narrowing for the all CNT cable. We conclude that the all CNT cable provides a sixty-five percent weight reduction with acceptable signal loss for low-bandwidth applications. As CNT manufacturers improve the conductivity of their material, the signal attenuation will decrease, allowing a broader set of cable applications (high bandwidth, power [3]).

Table 5. Waveform Outputs

Cable Type	Length (m)	Linear density (g/m)	Weight Reduction	1 MHZ	10 MHz
CNT conductor, CNT tape shield	5	9.06	65%		
Cu conductor, CNT tape shield	2	18.51	28.6%		
Cu conductor, Cu braid shield	5	25.94	--		

CONCLUSION

In recent years high volume quantities of CNT macroscopic materials have entered the commercial market, creating an opportunity to leverage low density materials to create new products with dramatic weight savings over existing cables. Candidate materials were selected based on electrical conductivity, tensile strength, and ability to be used in existing manufacturing tool sets. Two types of low bandwidth cables – MIL STD 1553B and LVDS twisted pair were built incorporating CNT materials and their electrical performance was compared to copper standards. At 1 MHz differences are minimal; at 10MHz the all CNT constructions exhibit signal attenuation that falls into an acceptable range depending upon the application lengths and requirements.

REFERENCES

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[3] S. E. Harvey, "Carbon as Conductor: A Pragmatic View," *Proceedings of the 62nd IWCS Conference*, pp 558-562, November 2012.